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A SERIES OF TEXTBOOKS FOR PERSONS ENGAGED IN THE ENGINEERING PROFESSIONS AND TRADES OR FOR THOSE WHO DESIRE INFORMATION CONCERNING THEM. FULLY ILLUSTRATED AND CONTAINING NUMEROUS PRACTICAL EXAMPLES AND THEIR SOLUTIONS

ELECTRICITY AND MAGNETISM
THEORY OF DIRECT-CURRENT GENERATORS AND MOTORS
DIRECT-CURRENT GENERATORS
DIRECT-CURRENT MOTORS
RESISTANCE MEASUREMENTS
DIRECT-CURRENT MEASURING INSTRUMENTS
ALTERNATING CURRENTS
ALTERNATORS
TRANSFORMERS
ALTERNATING-CURRENT RECTIFIERS
ALTERNATING-CURRENT MOTORS AND SYNCHRONOUS CONVERTERS
INDUSTRIAL MOTOR APPLICATIONS
STORAGE BATTERIES

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PREFACE

The volumes of the International Library of Technology are made up of Instruction Papers, or Sections, comprising the various courses of instruction for students of the International Correspondence Schools. The original manuscript for each Instruction Paper is prepared by a person thoroughly qualified, both technically and by experience, to write with authority on his subject. In many cases the writer is regularly employed elsewhere in practical work and writes for us during spare time. The manuscripts are then carefully edited to make them suitable for correspondence work.

The only qualification for enrolment as a student in these Schools is the ability to read English and to write intelligibly the answers to the Examination Questions. Hence, our students are of all grades of education, and our Instruction Papers are, therefore, written in the simplest possible language so as to make them readily understood by all students. If technical expressions are essential to a thorough understanding of the subject, they are clearly explained when first introduced.

The great majority of our students wish to prepare themselves for advancement in their vocations or to qualify for other and more congenial occupations. Their time for study is usually after the day's work is done and is limited to a few hours each day. Therefore, every effort is made to give them practical and accurate information in clear, concise form, and to make this information include all of the essentials but none of the non-essentials. To effect this result derivations of rules and formulas are usually omitted, but thorough and complete instructions are given regarding how, when, and under what conditions any particular rule, formula, or process should be

applied. Whenever possible one or more examples, such as would be likely to arise in actual practice, together with their solutions, are given for illustration.

As the best way to make a statement, explanation, or description clear is to give a picture or a diagram in connection with it, illustrations are very freely used. These illustrations are especially made by our own Illustrating Department in order to adapt them fully to the requirements of the text. Projection drawings, sectional drawings, outline drawings, perspective drawings, partly shaded or full shaded, are employed, according to which will best produce the desired result. Half-tone engravings are used only in those cases where the general effect is desired rather than the actual details.

In the table of contents that immediately follows are given the titles of the Sections included in this volume, and under each title is listed the main topics discussed. At the end of the volume will be found a complete index, so that quick reference can be made to any subject treated.

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CONTENTS

ELECTRICITY AND MAGNETISM
(PART 1)

INTRODUCTION

1. Manifestations of Electricity.—If a glass rod is rubbed with a piece of dry silk cloth, both the rod and the cloth, at the parts rubbed, will attract small bits of paper and string brought near them. If a stick of sealing wax is rubbed with a piece of dry flannel cloth, the surfaces rubbed together have the same property. A cat's fur rubbed in cold weather sparks with perceptible noise. During a thunder storm, lightning flashes across the clouds or between the clouds and the earth. All these are manifestations of electricity.

2. The name *electricity* comes from the Greek word *electron*, meaning *amber*, a substance that the ancients found would attract small particles of matter after it had been rubbed. Substances having this property are said to be *electrified*, or *charged*. **Electricity** may be defined as the cause of all electrical phenomena, or manifestations, though its exact nature is unknown. Much is known, however, as to its manifestations and its use, and the study of electricity applies chiefly to its uses and to what may be expected from it under different conditions.

3. Classes of Electricity.—Electricity at rest is called **static electricity**; this is the kind produced by rubbing glass with silk and wax with flannel. The name given the study of static electricity is **electrostatics.**

Electricity in motion is called **dynamic electricity,** and the name given to its study is **electrodynamics.** Substances

through which electricity flows readily are **conductors**, and those offering very high resistance to its flow are **non-conductors**, or **resistors**. Electricity moving through a conductor is **electric current.**

If an iron rod is grasped in one hand and a wooden rod of the same length in the other, and the free ends of these rods are held in a fire, the iron rod will become too hot to hold comfortably before the wooden rod has warmed. This is because iron conducts heat better than does wood. So it is with different substances in respect to electricity; some conduct it better than others.

ELECTRODYNAMICS

TERMS AND EXPRESSIONS

4. Electricity in motion is of chief interest and its study will be taken up first. Dynamic electricity is of two general classes, *direct-current electricity* and *alternating-current electricity*. Direct-current electricity flows continuously in one direction, and is therefore frequently called *continuous current*. Its strength may change, but its direction of flow does not change. Alternating-current electricity reverses its direction of flow many times per second. Alternating current will be fully discussed in future Sections. The statements in this Section apply particularly to the action of direct current, though some of these statements are true also of alternating current.

5. The **electric potential** of any part of a body refers to its electrical condition, or charge, compared with some other part, and a **difference of electric potential** between two points connected by a conductor causes flow of electricity, or current, from the point of high potential to the point of low potential. Difference of electric potential is *electric pressure*, and it may be compared with water pressure. If there is pressure in a water system and outlets are opened, water flows; but if the outlets are closed no water can flow. Likewise, electric pressure may exist with or without flow of electricity,

according to whether a conducting path is complete. Difference of electric potential is therefore that which causes or tends to cause flow of electricity, or electric current.

6. **Electromotive force** (abbreviated E. M. F.) is, strictly speaking, the force that establishes a difference of electric potential; but for practical purposes electromotive force and difference of electric potential may be considered as the same thing. Either causes or tends to cause electric current; the strength of current, or the rate of flow of electricity, depends on the strength of the electromotive force.

7. An **electric circuit** is a conducting path through which electric current will flow when the path is complete between points of different potentials. A complete path between such points is called a *closed circuit;* an incomplete path is called an *open circuit.*

8. The **direction of current** in an electric circuit is assumed to be from a condition called *positive*, or *high*, *potential* to a condition called *negative*, or *low*, *potential*. The signs + and − are used to indicate these two conditions. Thus electricity is said to flow from + to −.

9. **Electric resistance** is opposition to flow of electricity. Non-conductors have high resistance and conductors have low resistance. No known substance is wholly without resistance. The strength of current in a circuit depends not only on the electromotive force acting in the circuit, but also inversely on the resistance of the circuit; that is, the current increases with increased electromotive force, but decreases with increased resistance.

10. In general, the resistance of a long circuit or conductor is greater than that of a short one of the same size and material, and the resistance of a large body is less than that of a small one of the same material. Stated mathematically, *the resistance of a circuit or conductor depends directly on its length and inversely on its cross-sectional area*, or size if cut square across. The resistances of different materials are widely different, some

having very much higher resistance than others. The resistance of any given material is not the same at all temperatures.

11. Good conductors of electricity are made of materials having low resistance. Among such materials, arranged in order with the best conducting material first, are silver, copper, gold, aluminum, zinc, brass, phosphor-bronze, platinum, nickel, tin, steel, iron, lead, German silver, mercury, water, and carbon. Silver and gold are too expensive to be generally used for electric conductors. Copper, being plentiful and comparatively cheap, is in very general use, and aluminum is also much employed for long transmission lines.

12. An **insulator** is a non-conductor of such high resistance that practically no electricity can get through it. Among the best known insulating materials are glass, porcelain, rubber, mica, ebonite, dry paraffined wood, paper, vulcanized fiber, asbestos, pure asphalt, air, and oils. Insulators are used to support conductors and to keep the electricity confined to the circuits intended for it. For example, telegraph, telephone, and electric-light wires on poles are fastened to glass or porcelain insulators.

GENERATION OF ELECTROMOTIVE FORCE

13. The methods most commonly used to establish electromotive force are: (1) by chemical action in *primary cells;* (2) by heat action in *thermoelectric couples;* and (3) by magnetic induction in *dynamos*, or *electric generators*. Electric generators are used in power stations for electric-light and electric-railway work. They will be described in later Sections.

14. A **primary cell,** also called a *voltaic*, or *galvanic*, *cell*, is a combination of materials in which chemical action establishes electromotive force as soon as the materials are properly combined. Fig. 1 shows a simple primary cell consisting of a copper plate C and a zinc plate Z partly immersed in liquid in a glass jar A. Under such conditions, electromotive force is established between the plates, and if they were electrically connected outside the liquid, as would be the case if the

conductors shown attached to the plates were joined together, electricity would flow from copper to zinc outside the liquid and from zinc to copper through the liquid. When electricity flows through such a combination, some of the water in the liquid is separated, or decomposed, into two gases, hydrogen and oxygen. The hydrogen gathers on the surface of the copper plate, where it appears to be small air bubbles. The oxygen combines chemically with some of the zinc, and the zinc plate therefore gradually wastes away.

15. The two solid materials in the simple cell, Fig. 1, are called **electrodes**, or *elements;* taken together, they form the **voltaic couple.** The liquid is called the **electrolyte.** The electrode from which electricity enters the electrolyte is the **anode,** and the electrode toward which electricity flows in the electrolyte is the **cathode;** thus, the zinc plate is the anode and the copper plate, the cathode.

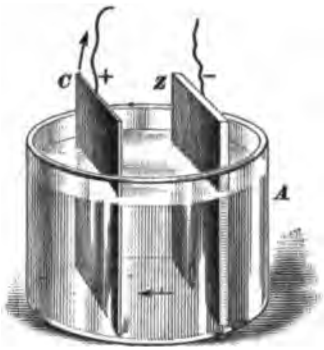


FIG. 1

The plates, the liquid between them, and the conductors connecting them outside the cell form a closed circuit. The part of this circuit inside the cell is the **internal circuit,** and the part outside the cell is the **external circuit.** Electricity flows from the anode to the cathode in the internal circuit and from the cathode to the anode in the external circuit. The flow continues in this direction until the cathode of a simple primary cell becomes covered with hydrogen gas. Such a flow of electricity is properly called continuous current, because its direction is unvarying and its flow steady. The hydrogen gas gradually gathers in small bubbles on the cathode, making the resistance of the circuit higher and the current less. When the cathode is completely covered the current ceases and the cell is said to be **polarized.**

16. Many different electrolytes are used in primary cells. The simplest are salt water or water with a little acid added.

The composition depends largely on the service for which the cell is intended. Electrolytes in commercial cells usually contain some substance that absorbs hydrogen or prevents it from gathering on the cathode. Such a substance is called a **depolarizer.**

17. A **primary battery** is a group of primary cells so connected electrically that either their electromotive forces or their currents are added. The conductors attached to the plates are the *cell terminals*, and these terminals can be joined in many ways. Primary batteries are used in telegraph, telephone, and signal work.

18. When two dissimilar metals are joined and their joint heated or cooled, electromotive force is established. The name *thermoelectromotive force* is applied, the word *thermo* being derived from a Greek word meaning heat; the current resulting when this force acts in a closed circuit is called *thermoelectric current.* Such a combination of metals is called a **thermoelectric couple** and several such couples together form a **thermoelectric pile.**

In order to establish thermoelectromotive force, the temperature of the couple or the pile must differ from that of the rest of the circuit of which it forms a part. If higher, the force acts in one direction; if lower, the force acts in the other direction.

19. The chief use of thermoelectromotive force is to indicate high temperatures by means of a **pyrometer,** which is a device consisting of an indicating instrument in circuit with a thermoelectric couple or pile. The couple or the pile is so arranged that it can be thrust into the place where the temperature is to be measured and the current thus set up through the instrument causes the needle, or hand, to deflect over a scale on which the temperature can be read. Temperatures in furnaces and ovens can be readily indicated in this way when no other method would serve the purpose. The indicator can be placed at a safe distance from the heat.

ELECTRICAL UNITS

QUANTITY OF ELECTRICITY

20. Measurement of Electricity.—Electricity is measured by its effects, or the work it does; the greater the effect, or the work done, the greater is the quantity of electricity. When it flows through the electrolyte of a voltaic cell, for example, some of the water is decomposed into gases, and the greater the quantity of electricity the greater is the formation of gas. When electricity is caused to flow through an electrolyte containing a metal in solution, some of the metal is deposited on one of the electrodes, the amount being proportional to the quantity of electricity. This is the way in which metallic articles, such as table ware, are plated.

21. The **coulomb** *is the unit quantity of electricity*, and is the quantity that deposits .00118 gram,* or .01725 grain,* of metallic silver from a carefully prepared electrolyte containing silver dissolved in nitric acid. This statement is true regardless of the time required for making this deposit.

CURRENT

22. The **ampere** (abbreviated amp.) *is the practical unit rate of flow of electricity*, or *unit current*, and is the rate when 1 coulomb flows each second; that is, *amperes equals coulombs per second*. The quantity of electricity in coulombs divided by the time in seconds required for this quantity to flow equals the rate of flow in amperes. One *milliampere* is $\frac{1}{1000}$ ampere; 1,000 milliamperes equals 1 ampere.

23. Conversely, if electricity is flowing at the rate of 1 ampere, then 1 coulomb flows per second, and the total number of coulombs equals the product of the number of amperes and the number of seconds. In other words, coulombs $=$ amperes $\times$ seconds, or ampere-seconds.

*Grams and grains are explained in a later Section.

24. In practical work, electric current is measured by means of an instrument called an **ammeter,** of which Fig. 2 shows one type. The ammeter is connected in circuit by inserting the ends of conductors in the openings in the two binding posts and clamping them with the thumbscrews at the tops of the posts. The current in the circuit causes the pointer to deflect over the scale to a figure indicating the strength of current in amperes or milliamperes.

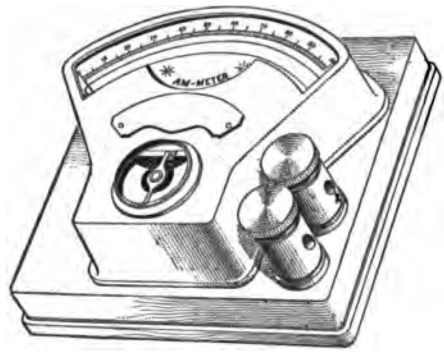


FIG. 2

RESISTANCE

25. The **international ohm** *is the practical unit of electric resistance*, and is determined by the resistance of a column of mercury of specified dimensions or by a standard ohm coil. These standards are of interest only in making accurate scientific measurements; for general practical work, use is made of instruments that indicate either the resistance in ohms or other measurements from which the resistance can be calculated. Such instruments are explained in other Sections. The word *ohm* as generally used in discussing electric circuits refers to the international ohm.

ELECTROMOTIVE FORCE

26. The **volt** *is the practical unit of electromotive force*, and is the electromotive force that will cause electricity to flow at the rate of 1 ampere through a circuit with a resistance of 1 ohm. Because of the name of its unit, electromotive force is commonly called **voltage,** and the word voltage will be much used in referring to electromotive force.

27. In practical work, voltage is measured by means of an instrument called a **voltmeter.** This instrument has much

the same appearance as an ammeter. Voltmeters also are made in many styles, or types, and for many different capacities, or ranges of voltage; a type much used is shown in Fig. 3.

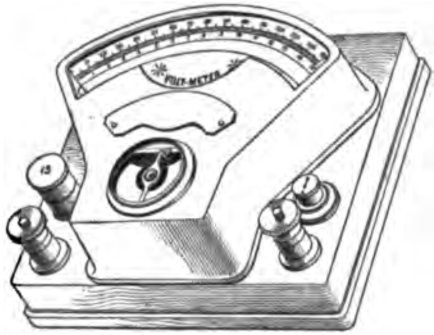


FIG. 3

ELECTRICAL WORK

28. The **joule** *is a unit of electric work*, and is the work done when 1 coulomb of electricity flows under a pressure of 1 volt; the time required makes no difference. The work, in joules, done in any circuit is equal to the product of the number of coulombs of electricity and the number of volts of electromotive force. As coulombs = ampere-seconds, joules = volts × amperes × seconds, or volt-ampere-seconds.

ELECTRIC POWER

29. The **watt** *is a unit of electric power* and is the rate of work when 1 joule is being done each second; that is, watts = joules per second, or joules ÷ seconds. Then the following is true:

$$\text{watts} = \frac{\text{joules}}{\text{seconds}} = \frac{\text{volts} \times \text{amperes} \times \text{seconds}}{\text{seconds}} = \text{volts} \times \text{amperes}$$

Let p = power, in watts;
E = electromotive force, in volts;
I = current, in amperes.

Then, $$p = E\,I$$

This formula is very important and should be remembered.

EXAMPLE 1.—What is the power, in watts, in a circuit in which the current is 12 amperes and the electromotive force 25 volts?

SOLUTION.—Here, $I = 12$ and $E = 25$; therefore, $p = 25 \times 12 = 300$ watts. Ans.

EXAMPLE 2.—If the power in a circuit is 550 watts and the voltage 110, what is the current in amperes?

SOLUTION.—Here $550=110\times I$; therefore, $I=550\div 110=5$ amp. Ans.

30. The **kilowatt** (abbreviated K. W.) is also a unit of electric power, and is equal to 1,000 watts; watts ÷ 1,000 = kilowatts. If P = power in kilowatts, then

$$P=\frac{E\,I}{1{,}000}$$

EXAMPLE.—If an electric motor takes 25 amperes from a 220-volt circuit, what is the power, in kilowatts, taken?

SOLUTION.—Here, $E=220$ and $I=25$; therefore,

$$P=\frac{220\times 25}{1{,}000}=5.5 \text{ K. W.} \quad \text{Ans.}$$

31. The **watt-hour** (abbreviated W.-hr.) and **kilowatt-hour** (abbreviated K.-W.-hr.) are units used to express either work or energy; each of these units is the product of a unit rate of work, or power, and a unit of time. Electric energy is nearly always bought and sold in kilowatt-hours, which are merely the product of the power, in kilowatts, and the time, in hours.

Let w = work, in watt-hours;
W = work, in kilowatt-hours;
p = power, in watts;
P = power, in kilowatts;
T = time, in hours.

Then,

$$w=p\,T \qquad (1)$$

$$W=P\,T \qquad (2)$$

EXAMPLE.—If work is being done in a circuit at the rate of 1,000 watts, (*a*) how many watt-hours will be done in 5 hours? (*b*) how many kilowatt-hours will be done in the same time?

SOLUTION.—(*a*) Apply formula **1**. Thus, $p=1{,}000$ and $T=5$; therefore, $w=1{,}000\times 5=5{,}000$ W.-hr. Ans.

(*b*) Apply formula **2**. As 1,000 watts = 1 K. W. and in this case also $T=5$, $W=1\times 5=5$ K.-W.-hr. Ans.

32. The relation between the watt-hour and the joule, both units of work, is shown by reducing the watt-hour to

watt-seconds, or joules. One hour contains 3,600 seconds; therefore, 1 watt-hour = 3,600 watt-seconds, or joules, or

$$\textit{watt-hours} = \textit{joules} \div 3{,}600$$

HEAT, WORK, AND POWER UNITS COMPARED

33. When work of any kind is done, heat is developed. Some work is required to turn the wheels of a machine, even when the machine is doing no useful work. In this case, practically all the work required to run the idle machine is converted into heat at the bearings. Every mechanic knows that the bearings of machinery must be kept lubricated in order to reduce friction and consequent heating. Too much friction causes overheated bearings; that is, too much work is converted into heat.

34. The *unit of heat* generally used in the United States and Canada is the **British thermal unit** (abbreviated B. T. U.); for practical purposes, it may be defined as the quantity of heat required to raise the temperature of 1 pound of pure water 1 degree (1°) Fahrenheit (F.). The Fahrenheit thermometer is the one generally used for measuring the temperature of the air, and the sign (°) means degree or degrees. The quantity of heat necessary to raise the temperature of any quantity of water may therefore be considered as equal to the product of the weight of water, in pounds, and the change of temperature, in degrees Fahrenheit.

Let H = heat, in British thermal units;
w = weight of water, in pounds;
t = change of temperature, in degrees Fahrenheit.

Then, $$H = w\,t$$

EXAMPLE.—How many British thermal units of heat are required to raise the temperature of $8\frac{1}{3}$ pounds (1 gallon) of water from 32° F. to 212° F.?

SOLUTION.—The change in temperature $t = 212 - 32 = 180°$, and the weight $w = 8\frac{1}{3}$. By the formula,

$$H = 8\tfrac{1}{3} \times 180 = 1{,}500 \text{ B. T. U.} \quad \text{Ans.}$$

NOTE.—The **calorie** a unit of heat in use in some countries, is $\frac{1}{252}$ B. T. U.; that is, 1 B. T. U. = 252 calories.

35. Mechanical Equivalent of Heat.—By arranging paddles in a vessel of water and a falling weight acting through a system of pulleys to rotate the paddles, the scientist Joule measured both the work done in rotating the paddles and the temperature rise of the water. He found that 778 foot-pounds of work has the same heating effect as 1 British thermal unit. In honor of its discoverer, 778 foot-pounds is called **Joule's mechanical equivalent of heat.** The relation between mechanical work and heat is therefore expressed by the formula

$$\textit{foot-pounds} = 778 \times \text{B. T. U.}$$

EXAMPLE 1.—How many foot-pounds of work are equivalent to the heat required to raise the temperature of 50 pounds of water 18° F.?

SOLUTION.—According to the formula of Art. **34**, $H = 50 \times 18 = 900$ B. T. U. and according to the preceding equation,

$$\text{foot-pounds} = 778 \times 900 = 700{,}200. \quad \text{Ans.}$$

EXAMPLE 2.—If 38,900 foot-pounds of work is converted into heat, how much will it raise the temperature of 10 pounds of water?

SOLUTION.—As ft.-lb. $= 778 \times$ B. T. U., $38{,}900 = 778 \times$ B. T. U., and B. T. U. $= 38{,}900 \div 778 = 50$. To raise the temperature of 10 lb. of water 1° F. requires 10 B. T. U., and 50 B. T. U. will raise it $50 \div 10 = 5°$ F. Ans.

36. Heat and Electrical Work.—To produce the same heating effect as 1 British thermal unit requires 1,055 joules of electrical work. This equivalent was also first determined by Joule by arranging a conductor so that all the work done by electricity in it would be absorbed in liquid surrounding the conductor. He then measured the work and the change of temperature of the liquid and divided the number of joules of work by the number of degrees change of temperature. The relation between heat and electrical work is therefore expressed by the formula

$$\textit{joules} = 1{,}055 \times \text{B. T. U.}$$

EXAMPLE.—(*a*) If an electric heater carrying 12 amperes at 110 volts is submerged in 22.5 pounds of water for 30 minutes (1,800 seconds), how much heat will be applied to the water? (*b*) What will be the final temperature of the water if its initial temperature is 35° F.?

SOLUTION.—(*a*) To apply the formula, the work in joules must be determined. As joules = volts × amperes × seconds, the number in this case is

$110 \times 12 \times 1{,}800 = 2{,}376{,}000$. By the formula, $2{,}376{,}000 = 1{,}055 \times$ B. T. U. Therefore,

B. T. U. $= 2{,}376{,}000 \div 1{,}055 = 2{,}252$, approx. Ans.

(*b*) Since 22.5 B. T. U. are required to raise the temperature of 22.5 pounds water 1°, the total rise will be $2{,}252 \div 22.5 = 100°$ F., approximately, and the final temperature will be $100 + 35 = 135°$ F. Ans.

37. Mechanical and Electrical Work.—Since 778 foot-pounds equals 1 British thermal unit, and 1,055 joules also equals 1 British thermal unit,

$$778 \text{ foot-pounds} = 1{,}055 \text{ joules},$$

$$1 \text{ foot-pound} = \frac{1{,}055}{778} = 1.356 \text{ joules, approximately,}$$

and

$$1 \text{ joule} = \frac{778}{1{,}055} = .737 \text{ foot-pound, approximately}$$

Therefore,
$$\textit{joules} = 1.356 \times \textit{foot-pounds}$$
$$\textit{foot-pounds} = .737 \times \textit{joules}$$

Example 1.—How many joules are equivalent to 500 foot-pounds?

Solution.—Joules $= 1.356 \times$ ft.-lb. $= 1.356 \times 500 = 678.0$. Ans.

Example 2.—A current of 10 amperes from a 110-volt circuit for 30 minutes (1,800 seconds) is equivalent to how many foot-pounds?

Solution.—Joules = volts $\times$ amp. $\times$ sec. $= 110 \times 10 \times 1{,}800 = 1{,}980{,}000$, and ft.-lb. $= .737 \times$ joules $= .737 \times 1{,}980{,}000 = 1{,}459{,}260$. Ans.

38. Mechanical and Electrical Power.—Since 1 foot-pound equals 1.356 joules, 1 foot-pound per second equals 1.356 joules per second, or watts. One horsepower equals 550 foot-pounds per second, or 550×1.356 equals 745.8, or approximately 746, watts; then,

$$\text{H. P.} = \frac{\textit{watts}}{746} = \frac{\textit{volts} \times \textit{amperes}}{746}$$

Example 1.—What is the horsepower equivalent of 400 amperes at 2,200 volts?

Solution.— $\text{H. P.} = \dfrac{2{,}200 \times 400}{746} = 1{,}179.6$, approx. Ans.

EXAMPLE 2.—If a motor takes 94.7 amperes from a 220-volt circuit and converts 89.5 per cent. of the electric power received into mechanical power, what is the output in horsepower?

NOTE.—As commonly expressed, the motor efficiency is 89.5 per cent.

SOLUTION.—The power input in watts is $94.7 \times 220 = 20{,}834$ and the output in watts is $20{,}834 \times .895 = 18{,}646.4$. The output in horsepower is $18{,}646.4 \div 746 = 25$, nearly. Ans.

The work can be indicated thus: $\frac{220 \times 94.7 \times .895}{746} = 25.$

EXAMPLE 3.—If a motor does work at the rate of 17 horsepower, that is, the motor output is 17 horsepower, and this is only .875 of the electrical power received by the motor, how much current does it take from a 220-volt circuit?

SOLUTION.—As only .875 of the electrical-power input is converted into mechanical-power output, the input in horsepower is $17 \div .875$, or $\frac{17}{.875}$. Then, according to the equation, $\text{H. P.} = \frac{\text{volts} \times \text{amp.}}{746}$, or $\frac{17}{.875} = \frac{220 \times \text{amp.}}{746}$; $\text{amp.} = \frac{17 \times 746}{.875 \times 220} = 65.9$. Ans.

EXAMPLES FOR PRACTICE

1. A large room is lighted by 12 fixtures each containing 7 lamps. The current required to light each lamp is .5 ampere from a 110-volt circuit. What is the power, in watts, when all the lamps are lighted?
Ans. 4,620

2. At 3 cents ($.03) per kilowatt-hour, what is the cost of lighting all the lamps referred to in example 1 for 1,000 hours? Ans. $138.60

3. At 3 cents per kilowatt-hour, how much could be saved in 1,000 hours by substituting for the fixtures in example 1, 24 tungsten lamps requiring $1\frac{4}{11}$ amperes each from a 110-volt circuit? Ans. $30.60

4. If the work equivalent to lifting 10,000 pounds 200 feet were converted into heat, how much would it raise the temperature of $16\frac{2}{3}$ pounds (2 gallons) of water? Ans. 154.2° F.

5. An electric heater taking 5 amperes at 110 volts is immersed in $8\frac{1}{3}$ pounds of water. How many seconds will be required to raise the temperature of the water from 32° F. to 180° F.? Ans. 2,366−, approx.

NOTE.—Find the number of British thermal units as in Art. **34**, and the number of joules as in Art. **36**, and remember that joules = watt-seconds.

6. If an engine works at the rate of 120 horsepower to drive an electric generator, and the generator converts .9 of this power into electricity at 220 volts, what is the current in the generator? Ans. 366 amp., approx.

7. How many horsepower must a waterwheel develop to drive an electric generator that delivers 1,000 amperes at 500 volts if .92 of the mechanical power delivered to the generator is converted into electric power?
Ans. 729

8. At 4 cents ($.04) per kilowatt-hour, what will be the yearly cost of electric energy to run a motor driving the machines of a wood-working plant if the motor develops an average of 6 horsepower for 2,500 hours per year and converts .8 of the electric power received into mechanical-power output? Ans. $559.50

ELECTRIC CIRCUITS

CIRCUIT TERMS

39. As already explained, an electric circuit is *closed* if it affords a continuous path for the flow of electricity and *broken*, or *open*, if the path is only partly complete. Thus, when an electric lamp is switched on, the circuit through the lamp is closed and the lamp lights; when switched off, the circuit through the lamp is open and no light is given off. An electric circuit is said to be *grounded* when any part of it is in electrical connection with the earth or with a conductor leading to the earth. Thus, when an electric-light wire rubs against a water pipe until the insulating cover on the wire is worn through so that the copper wire touches the pipe, the lighting circuit is grounded to the water pipe.

The *external part* of a circuit is the part outside of the source of electromotive force, or external to it; the *internal part* is the part within the source of electromotive force, as illustrated by the voltaic cell.

SERIES GROUPING

40. Electric conductors, sources of electromotive force, or devices using electricity can be connected in several ways. When the connections are such as to form only one path for the flow of electricity, the connection, or grouping, is in **series.**

For example, Fig. 4 represents a closed circuit consisting of simple voltaic cell B and four conductors a, b, c, and d connected in series; that is, electricity can flow from the positive terminal of the cell to the negative terminal through only one path. An opening in any part of this series circuit would prevent all flow of electricity.

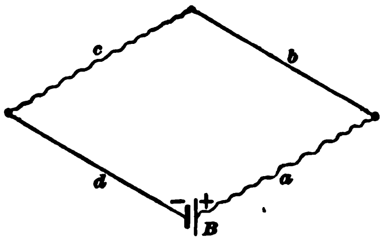


FIG. 4

41. Sources of electromotive force are connected in series when their terminals are joined so that the voltages are added. Fig. 5 represents six voltaic cells connected in series; the positive terminal of each cell is joined with the negative terminal of the next cell in the series. The circuit is represented open and the arrows show the direction of electromotive force, or the direction in which electricity would flow if the circuit were closed. In this case, there would be only one path for the current, and the total electromotive force acting in the path, or circuit, would be the sum of the electromotive forces of all the six cells.

Figs. 4 and 5 serve to show the usual, or conventional, method of representing electric-battery cells; a short heavy line represents the negative terminal of a cell and a longer lighter line the positive terminal.

42. If the terminals of one cell, Fig. 5, were interchanged so that its positive terminal were joined to the positive terminal of another cell and its negative terminal to another negative terminal, this cell would not be in true series with the others, but in opposition to them. Its voltage would then be deducted from the sum of the voltages of the others. For true series connection, sources of electromotive force must not only be in the same circuit but must agree in direction.

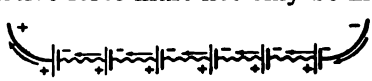


FIG. 5

43. Resistance of Series Group.—The resistance of several conductors connected in series is equal to the sum of the resistances of the conductors.

For example, if, in Fig. 4, the resistances of conductor $a=8$ ohms, $b=12$, $c=22$, and $d=34$, then the four conductors in series have a resistance of $8+12+22+34=76$ ohms, which is the external resistance of the circuit. If the internal resistance between the terminals of the battery B is 5 ohms, the total resistance of the circuit is $76+5=81$ ohms.

PARALLEL GROUPING

44. A circuit that is divided into two or more branches, each branch transmitting part of the current, is a **derived,** or **shunt, circuit,** and the separate branches are said to be connected in **parallel,** or **multiple.** Fig. 6 shows a closed divided circuit consisting of a source of electromotive force B, and conductors a, b, c, and d. Conductors b and c afford two current paths between conductors a and d, and are therefore in parallel. Either path b or c could be broken without interfering with the flow of electricity through the other path, because each is independent of the other. The arrows indicate direction of current.

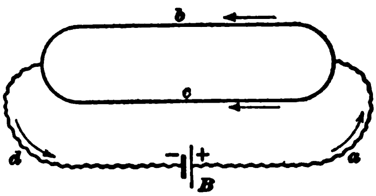


FIG. 6

45. Sources of electromotive force are connected in parallel, or multiple, when all their positive terminals are joined to one conductor and all their negative terminals to another conductor, as in Fig. 7. The electromotive force between the two conductors is the same as that of any one of the equal sources. The arrows indicate the directions of the electromotive forces, or the direction in which electricity would flow if the external circuit were closed. The current in the external circuit would then be equal to the sum of all the currents from the several sources of electromotive force. For example, if the six sources of electromotive force indicated in Fig. 7 were equal,

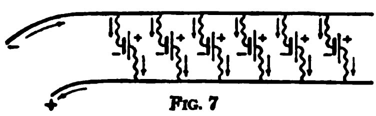


FIG. 7

and if the current through each source were 2 amperes, the current in the external circuit, when closed, would be 12 amperes.

46. Resistance of Similar Conductors in Parallel Groups.—In Fig. 6, the two paths *b* and *c* together are larger, and hence lower in resistance, than either path would be alone. Joining in parallel two conductors of the same material and of the same size and length is equivalent to making one conductor twice as large as either one of the two joined, and doubling the size of the conductor divides its resistance by two.

In a like manner, adding the third conductor of the same size and material would make the combination three times as large as any one of the three, and the resistance one-third as much. When several conductors of the same size, length, and materials are joined in parallel, the combined resistance of all of them is equivalent to the resistance of each conductor divided by the number joined. By formula,

$$R = \frac{r}{n}$$

in which R = combined resistance of a number of equal conductors joined in parallel;
r = resistance of each conductor;
n = number of conductors.

EXAMPLE.—What is the combined resistance of a group of 11 incandescent lamps in parallel, if the resistance of each lamp is 220 ohms?

SOLUTION.—By the formula, $R = \frac{220}{11} = 20$ ohms. Ans.

47. Conductance.—The conductance of a substance is its ability to conduct electricity. Conductance is the reciprocal of resistance and is usually expressed in units designated by the word **mho**, which is *ohm* spelled backwards. If the resistance of a conductor is 10 ohms, its conductance is $\frac{1}{10}$ mho; if the resistance is 25 ohms, the conductance is $\frac{1}{25}$ mho; if the resistance is $\frac{1}{2}$ ohm, the conductance is 2 mhos; if the resistance is r ohms, the conductance is $\frac{1}{r}$ mhos; and so on. Conversely, the resistance is the reciprocal of the conductance. Thus, if the

conductance is $\frac{1}{r}$ mhos the resistance is r ohms; if the conductance is r mhos the resistance is $\frac{1}{r}$ ohms.

48. Resistance of Unlike Conductors in Parallel Groups.—When conductors are joined in parallel, their individual conductances should be added to get the combined conductance. The reciprocal of this combined conductance is the resistance of the group. For example, if two conductors with resistances of 2 ohms and 3 ohms, respectively, are joined in parallel, their combined conductance is $\frac{1}{2}$ mho$+\frac{1}{3}$ mho $=\frac{5}{6}$ mho, and their combined resistance is the reciprocal of $\frac{5}{6}$, or $\frac{6}{5}$ ohms.

Let R = combined resistance of several conductors in parallel;

r, r_1, r_2, etc. = individual resistances;

G = combined conductance in parallel.

Then,
$$G=\frac{1}{R}=\frac{1}{r}+\frac{1}{r_1}+\frac{1}{r_2}, \text{ etc.} \qquad (1)$$

$$R=\frac{1}{G}=\frac{1}{\frac{1}{r}+\frac{1}{r_1}+\frac{1}{r_2}, \text{ etc.}} \qquad (2)$$

Example 1.—Find: (*a*) the conductance, and (*b*) the resistance of four conductors in parallel, their individual resistances being $\frac{1}{3}$ ohm, 2 ohms, 3 ohms, and 6 ohms.

Solution.—Here, $r=\frac{1}{3}$ and $\frac{1}{r}=3$, $r_1=2$ and $\frac{1}{r_1}=\frac{1}{2}$, $r_2=3$ and $\frac{1}{r_2}=\frac{1}{3}$, and $r_3=6$ and $\frac{1}{r_3}=\frac{1}{6}$.

(*a*) By formula **1**,

$$G=3+\tfrac{1}{2}+\tfrac{1}{3}+\tfrac{1}{6}=4 \text{ mhos. Ans.}$$

(*b*) By formula **2**,

$$R=\frac{1}{G}=\tfrac{1}{4} \text{ ohm. Ans.}$$

Example 2.—Find the combined resistance of four conductors in parallel, their resistances in ohms being 5, 8, 16, and 80.

Solution.—By formula **2**,

$$R=\frac{1}{\frac{1}{5}+\frac{1}{8}+\frac{1}{16}+\frac{1}{80}}=\frac{1}{\frac{32}{80}}=\frac{1}{\frac{2}{5}}=\frac{5}{2}=2\tfrac{1}{2} \text{ ohms. Ans.}$$

PARALLEL-SERIES AND SERIES-PARALLEL GROUPING

49. When devices are connected in several series and these series are connected in parallel, as in Fig. 8, the devices are said to be connected in **parallel series**, or **multiple series.** If the devices are battery cells, as indicated, each series should contain the same number of similar cells; the positive terminals of all the series are connected to one conductor and the negative terminals to the other. The electromotive force between the two conductors is the same as that of any series, and if the external circuit were closed the current would be the sum of the currents in all the series.

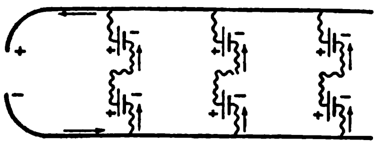


FIG. 8

50. Series-parallel connection means literally a *series of parallels*, as indicated in Fig. 9, in which three groups *a*, *b*, and *c* are connected in series, each group having four devices in parallel.

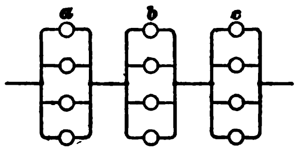


FIG. 9

51. The expressions *parallel series* and *series-parallel* are frequently used without distinction as to meaning, and the distinction is not usually of great importance in practice. Circuits including both methods of connection are sometimes used, as in Fig. 10, in which each part (*a*) and (*b*) is a parallel-series connection and the two parts connected in series form part of a series-parallel circuit.

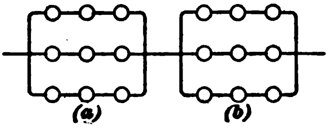


FIG. 10

52. Resistance With Combination Grouping.—The combined resistance of devices or conductors grouped in parallel series or series-parallel is obtained by combining the processes already given for series and for parallel circuits. That is, add the resistances of devices in series and the conductances of devices in parallel.

For example, if each device in Fig. 9 has a resistance of 3 ohms, the conductance of each is $\frac{1}{3}$ mho and the conductance of the four devices in each group is $4\times\frac{1}{3}=\frac{4}{3}$ mho. The resistance of each group is therefore $\frac{3}{4}$ ohm, and of the three groups in series, $3\times\frac{3}{4}=\frac{9}{4}$, or $2\frac{1}{4}$, ohms. If the four devices in each group have the same resistance and no two groups have the same resistance, the resistance of each group can be found separately and the resistances of the three groups added to find the total resistance.

THREE-WIRE CIRCUITS

53. A three-wire circuit, or **system,** is an arrangement of three conductors in parallel, two called *outside conductors* and the third the *neutral conductor*. The voltage between the two outside conductors is double the voltage between the neutral and either outside conductor. Fig. 11 represents part of such a system with a pressure of 230 volts across the outside wires and one of 115 volts between the neutral and either outside wire. Such systems are much used for electric lighting. The lamps are connected between the neutral and the outside wires, as at *l*, and when electric motors are run from the same circuit they are usually connected across the outside wires, as at *m*.

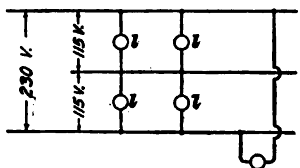


FIG. 11

If the devices are so distributed that the same current is taken from each side of the system, that is, each side of the neutral wire, the system is said to be **balanced.** The neutral wire then carries no current. This is the condition indicated in Fig. 11, in which the same number of lamps are shown connected with each side of the circuit. When the devices are so connected that more current is used on one side of the system than the other, the system is said to be **unbalanced.** The neutral wire then carries the unbalanced current, or the excess used on the more heavily loaded side.

OHM'S LAW

54. The substance of Ohm's law has already been given in the statement that flow of electricity increases with increased electromotive force and decreases with increased resistance. The law as applied to direct-current circuits can be easily remembered, thus: *The strength of current in any circuit is equal to the quotient of the electromotive force acting in the circuit divided by the resistance of the circuit.*

Let I = current;
E = electromotive force;
R = resistance.

Then,
$$I=\frac{E}{R}$$
is the statement of Ohm's law by formula. If the electromotive force is in volts and the resistance in ohms, the current is in amperes; that is,

amperes = volts ÷ ohms

If any two of these three quantities are known, the third can be found by transposing the equation $I=\frac{E}{R}$ so as to obtain either $E=IR$ or $R=\frac{E}{I}$.

Example 1.—If an electric lamp has a resistance of 220 ohms, what current will it carry when connected with a 110-volt circuit?

Solution.—Here $E=110$ volts and $R=220$ ohms; then, by applying the formula,

$$I=\frac{110}{220}=\frac{1}{2}\text{ amp. Ans.}$$

Example 2.—What is the resistance of a 550-watt, 110-volt electric flat iron?

Solution.—The first step is to find the current. As before explained, power in watts equals volts × amperes. Then, 550 watts = 110 × amp., and amp. = 550 ÷ 110 = 5. By Ohm's law, $5=\frac{110}{R}$ and, by transposition,

$$R=\frac{110}{5}=22\text{ ohms. Ans.}$$

EXAMPLE 3.—What voltage is necessary to cause a current of 5 amperes in a device having a resistance of 16 ohms?

SOLUTION.—By Ohm's law, $5=\frac{E}{16}$, and by transposition $80=E$, or $E=80$ volts. Ans.

55. Drop, or Fall, of Potential.—Ohm's law applies whenever direct-current electricity flows. Every conductor has resistance, and electric pressure $E=I\,R$ is required to cause flow of electricity in it. If the current I is constant and the resistance R uniform, the pressure E is proportional to the length of the conductor; that is, the longer the conductor, the greater is the pressure necessary to maintain the current. If 10 volts is necessary to establish 50 amperes of direct current in a conductor 1,000 feet long and of uniform resistance throughout its length, 5 volts will be required to establish the same current in a similar conductor 500 feet long, and 1 volt for a similar conductor 100 feet long.

The electromotive force necessary to maintain current in a circuit is the **drop of potential**, or the *voltage drop*, in that circuit. For example, 50 amperes in the circuit from a generator to a motor may cause a 10-volt drop in the circuit, so that the voltage at the motor terminals is 10 less than that at the generator terminals. If the generator voltage is 230, the voltage at the motor, or the voltage drop in the motor, will be 220. The voltage drop in conductors can always be calculated if the current and the resistance of the conductors are known, for $E=I\,R$.

EXAMPLE 1.—If electric lamps requiring 25 amperes at 110 volts are located 100 feet from a source of electromotive force and the current is led through conductors having a total resistance of $\frac{1}{5}$ ohm, (*a*) what voltage must be maintained at the source? (*b*) what is the voltage drop per foot of conductor?

SOLUTION.—(*a*) The total drop $E=I\,R$, or $25\times\frac{1}{5}=5$ volts; the source of electromotive force must therefore be $110+5=115$ volts. Ans.

(*b*) The voltage drop per foot is $5\div 200$ (100 feet each way) $=.025$ volt. Ans.

EXAMPLE 2.—With 12 amperes in a circuit of four parts with resistances as indicated in Fig. 12, (*a*) what is the voltage drop in each part? (*b*) what is the total voltage drop, or the voltage E?

SOLUTION.—(*a*) The voltage drop in *a* is $12\times\frac{1}{2}=6$; in *b*, $12\times\frac{1}{3}=4$; in *c*, $12\times\frac{1}{4}=3$; and in *d*, $12\times\frac{1}{6}=2$. Ans.

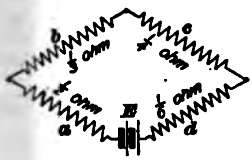


FIG. 12

(*b*) The total voltage drop, or the voltage *E*, is $6+4+3+2=15$. Ans.

EXAMPLE 3.—If an electric motor 500 feet from the source of electromotive force must be supplied with 5 amperes of current with a voltage drop of 12 in the line, (*a*) what must be the line resistance? (*b*) what is the resistance of each conductor?

SOLUTION.—(*a*) The line resistance $R=\frac{E}{I}=\frac{12}{5}=2.4$ ohms. Ans.

(*b*) The line has two conductors, and the resistance of each must be one-half of the total line resistance, or $2.4\div 2=1.2$ ohms. Ans.

56. Divided Circuits.—If a circuit is divided into several branches in parallel, each branch will carry current in accordance with Ohm's law, and the total current in the circuit will equal the sum of the currents in the branches. A divided circuit with the conditions shown in Fig. 13 will carry current in the 5-ohm branch $\frac{80}{5}=16$ amperes, in the 10-ohm branch $\frac{80}{10}=8$ amperes, and in the 20-ohm branch $\frac{80}{20}=4$ amperes. The total current in the circuit will then be $16+8+4=28$ amperes.

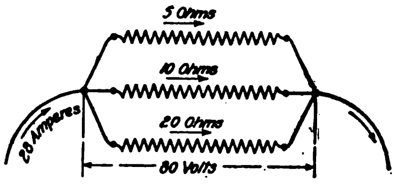


FIG. 13

The combined resistance of the three branches, Fig. 13, is found by adding their conductances and taking the reciprocal of the sum, as previously explained; namely, $\frac{1}{\frac{1}{5}+\frac{1}{10}+\frac{1}{20}}=\frac{1}{\frac{7}{20}}=\frac{20}{7}=2\frac{6}{7}$ ohms. The current set up by 80 volts in a $2\frac{6}{7}$-ohm circuit is $\frac{80}{2\frac{6}{7}}=80\times\frac{7}{20}=28$ amperes, which agrees with the number of amperes found by adding the currents in the three branches. The total current can therefore be found by either method.

EXAMPLES FOR PRACTICE

1. Two resistances of 30 and 20 ohms, respectively, are connected in parallel. Find: (*a*) their joint resistance; (*b*) their joint conductance.

Ans. $\begin{cases} (a) \ 12 \text{ ohms} \\ (b) \ \frac{1}{12} \text{ mho} \end{cases}$

2. Three groups of lamps are connected in series, each group consisting of four lamps of 220 ohms each in parallel; what is the total resistance across the three groups? Ans. 165 ohms

3. What voltage must be impressed upon a 22-ohm circuit in order to establish a current of 5 amperes? Ans. 110 volts

4. It is desired to limit the current through a 70-ohm device to 2 amperes from a 220-volt circuit. What must be the value of the additional resistance connected in series with the device? Ans. 40 ohms

5. Four resistances of 3, 5, 9, and 15 ohms, respectively, are connected in parallel across a 450-volt circuit. Determine: (*a*) the current through each branch; (*b*) the total current.

Ans. $\begin{cases} (a) \ 150, 90, 50, \text{ and } 30 \text{ amp.} \\ (b) \ 320 \text{ amp.} \end{cases}$

ELECTROSTATICS

ELECTRIC CHARGES

57. When a glass rod is electrified by rubbing it with silk, the charge resides on only the parts rubbed; if these parts are touched with anything through which electricity can pass to the ground, the charge instantly disappears. The same statements are true of charges established in any other way, as by rubbing wax with flannel or by the friction of leather belts on iron pulleys.

58. When an electrified glass rod is held near an insulated piece of light material, as a pith ball, Fig. 14, the material will be attracted; if allowed to touch the glass the ball will promptly swing away from it and will recede whenever the glass is brought near. If another pith ball is treated in the same way, the two balls will repel each other.

59. Sealing wax electrified by rubbing it with flannel will attract light pieces that have been repelled by the charge on the glass when rubbed with silk. For example, if the electrified wax is brought near the pith ball, Fig. 14, that has been charged and repelled by the glass, the ball will be attracted to the wax. The charge on the wax is therefore unlike that on the glass.

60. Two kinds of electric charges, or of static electricity, are thus illustrated. The names *positive* and *negative* are used to designate these charges. Neither can be developed without the other. The charge developed on glass when it is rubbed with silk is positive, and an equal negative charge is at the same time developed on the silk. A negative charge is developed on wax when it is rubbed with flannel, and an equal positive charge is simultaneously developed on the flannel.

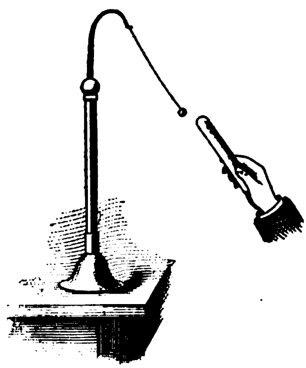


FIG. 14

61. Electrostatic Laws. Electric charges act according to the following laws:

1. When two dissimilar unelectrified substances are brought into contact, one assumes a positive and the other a negative condition.
2. An unelectrified body on coming into contact with an electrified body becomes electrified with a charge similar to that on the electrified body.
3. Similarly charged bodies repel each other; dissimilarly charged bodies attract each other.

62. Electric Series.—The accompanying list of substances, called the *electric series*, is arranged so that each substance is positive to all that follow it in the list and negative to all that precede it; that is, any substance receives a positive charge when rubbed or brought in contact with a substance the name of which occurs later in the list and a negative charge when rubbed with substances named earlier

Electric Series

1.	Fur	6.	Cotton	11.	Metals
2.	Flannel	7.	Silk	12.	Sealing wax
3.	Ivory	8.	Leather	13.	Resins
4.	Crystals	9.	The body	14.	Gutta percha
5.	Glass	10.	Wood	15.	Guncotton

in the list. For example, *glass* when rubbed with *fur* receives a *negative* charge, but when rubbed with *silk* receives a *positive* charge. In some cases, the charges are so small as to be scarcely perceptible.

63. Electrostatic Induction.—If a charged body is brought near an insulated body, a charge will be induced on the latter body, as is proved by the experiment illustrated in Fig. 15. Two conductors *a b* and *c* are supported on insulating stands, several pairs of pith balls being suspended from conductor *a b*. When conductor *c* is charged and brought near conductor *a b*, the pith balls separate, as shown, demonstrating that a charge is induced on conductor *a b*. This charge, being the same on all the balls, causes them to repel each other. When the two conductors are separated again, the balls fall to their original positions, showing that the charge has disappeared.

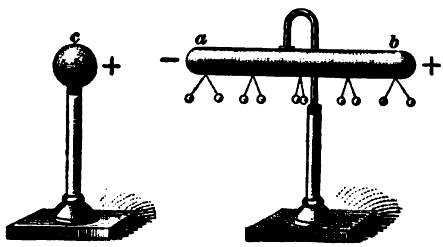


Fig. 15

When the two conductors are close together, the charge on conductor *c* attracts an opposite charge on the end *a* of conductor *a b* and repels electricity of the same kind to the end *b* farthest from *c*. The induced charge on conductor *a b*, being strongest at the ends, the pairs of balls at the ends separate more widely than those nearer the center. When conductor *c* is withdrawn, the two charges on conductor *a b* neutralize each other, and each pair of balls will again hang together. They can thus be made to separate and come together merely by moving a charged body close to conductor *a b* or away from it.

64. If two conductors, one heavily charged, are brought very near each other, the attraction between the opposite charges may become so strong that electricity in the form of a *spark* will jump through the space between the two bodies, exactly similar to a lightning discharge, except on a very small scale. In the case of lightning, opposite charges on adjacent clouds or on a cloud and the earth attract each other so strongly that a very large spark, or *flash*, of electricity jumps across the intervening air space, thus neutralizing some or all of the two charges.

When electricity passes through the insulating medium, for example, the air space separating charged conductors, the insulation is said to be *broken down*, or *punctured*. The insulation does not affect the influence of one charged body on another, but does prevent the discharge of electricity from one to the other until the attraction becomes strong enough to puncture the insulation. For example, a sheet of paper held between conductors *a b* and *c*, Fig. 15, does not influence the induction of a charge on *a b*; but a spark cannot pass between the two conductors until the attraction is strong enough to cause electricity to puncture the paper.

65. Static electricity sometimes accumulates on moving belts, owing to friction with pulleys, and it may become strong enough to cause slight shocks to persons near the belts or when touching the machines with which the belts are operating. In fact, if an electric generator or a motor in a dry room is insulated from the ground and belted, the charge may accumulate strong enough on the frame of the machine to puncture the insulation of the conductors. In order to avoid such accumulations, a grounded conductor can be placed where the belt will pass near it. The charge then escapes to the earth and is neutralized. Best results are obtained if metal points project from the conductor toward the belt; electricity escapes most readily to or from points. This fact explains why lightning rods and other conductors from which static electricity must escape are pointed.

CONDENSERS

66. An **electric condenser** is a device for accumulating, or condensing, electricity by the effect of electrostatic induction between conducting bodies separated by insulation.

An electric condenser is formed when any two conducting substances are separated by an insulating substance; for example, a glass plate with a sheet of tin-foil on each side is an electric condenser. The two metallic substances are termed the **plates**, and the insulating substance the **dielectric** of the condenser.

67. A wire strung on insulators and the earth or any conducting object connected with it are the two plates of a condenser, and the air or any other insulating substance separating the wire from the ground is the dielectric.

Subterranean or submarine cables are condensers; the conductor and the outer steel armor or lead covering are the two plates, and the insulating substance separating them, such as vulcanized rubber, paper, or jute, is the dielectric.

68. When electromotive force is applied to the terminals of a condenser, electricity flows into the condenser until the opposing, or counter, electromotive force of the condenser equals the applied electromotive force. The condenser is then said to be *charged*, and it will discharge through any circuit placed across its terminals. The **capacity** of a condenser has reference to the quantity of electricity that will flow into it with a given charging electromotive force. The voltage across the terminals of a condenser is a measure of the stress to which the dielectric is subjected, or the tendency to puncture the insulation. When a condenser is fully charged, the dielectric stress is equal to the charging voltage. A charged condenser is somewhat like a compressed spring; the spring tends to recoil as soon as it is released, and the charge on the condenser tends to escape the instant a discharge circuit is completed across its terminals.

69. Condensers are essential in some electric circuits. They are made by assembling in a mass, sheets of conducting material

separated by a dielectric, alternate conductors being connected with each terminal of the condensers, as indicated in Fig. 16. The sheets of conducting material are indicated at p, the dielectric at i, and the terminals at T. Each terminal and the sheets connected with it form a plate of the condenser.

70. Long transmission lines have considerable capacity as condensers, and this fact must be considered when installing and operating such lines. Serious accidents have happened owing to the discharge from such lines after they are disconnected from the electric generator that charged them. Operators, assuming that the disconnected line is *dead*, proceed to handle it or some device electrically connected with it and may receive fatal shocks due entirely to static electricity. This danger can arise only with high-voltage lines; therefore, after such lines are disconnected from the generator, they should be thoroughly grounded before handling them.

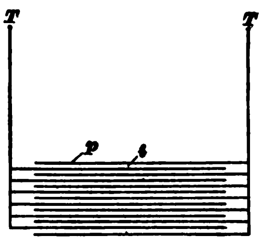


FIG. 16

ELECTRICITY AND MAGNETISM
(PART 2)

PERMANENT MAGNETISM

MAGNETS AND MAGNETIC PROPERTIES

1. A **natural magnet** is a piece of ore (a natural substance containing a mineral) that has the property of attracting pieces of iron, steel, and a few other metals. This ore was first discovered in the province of Magnesia, Asia; the peculiar property was therefore called *magnetism*, and the name *magnet* was applied to a piece of ore possessing the property.

Later the discovery was made that if such magnets were suspended so that they could turn freely, all would come to rest in positions pointing north and south. Small bars of the ore were thus used to guide ships over the seas. They were therefore called *lodestones* (leading stones), a name that is also applied to the ore. These lodestones were thus the forerunners of the modern compass.

2. A bar or a needle of hardened steel rubbed with a lodestone acquires properties similar to those possessed by the lodestone, and is called an **artificial magnet**. Artificial magnets that retain the characteristics of the lodestone for a considerable period of time, are called **permanent magnets**. Fig. 1 shows a common form of permanent magnet, consisting of a bar of steel bent into the shape of a horseshoe and then hardened and magnetized. A piece of soft iron called an *armature*, or *keeper*, placed across the two free ends, helps to

retain the magnetism. Artificial magnets are also made in the form of a straight bar, as shown in Fig. 2.

3. If a bar magnet is dipped into iron filings, the filings are attracted toward the two ends and adhere there in tufts, as in Fig. 3, while toward the center of the bar no such tendency is noticeable. That part of the magnet where no apparent magnetic attraction exists is called the **neutral region,** and the parts around the two ends are called **poles.** An imaginary line drawn through the center of the magnet from end to end, connecting the two poles is called the *axis of magnetism.*

FIG. 1

4. A magnetized steel needle of the form shown in Fig. 4, resting on a fine point so as to turn freely in a horizontal plane, is called a **compass.** When not in the vicinity of iron, steel, or other magnets, such a needle comes to rest with one end pointing toward the north and the other toward the south. The end pointing northwards is therefore called the *north pole,* and the opposite end is called the *south pole,* meaning, respectively, *north-seeking* and *south-seeking.* Every magnet has two poles, and the letters N and S appearing on illustrations of magnets are to indicate north and south polarity.

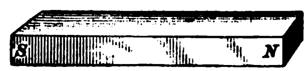


FIG. 2

5. Magnetic Attractions and Repulsions.—A general law applying to all magnets is that *like magnetic poles repel each other while unlike poles attract each other.* If two bar magnets are suspended so as to swing freely and are brought near together, the repulsion between like poles and the attraction between unlike poles will cause them to turn until unlike poles are as near each other as possible.

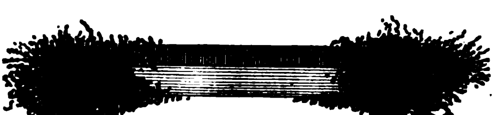


FIG. 3

The earth is a great magnet whose magnetic poles coincide nearly, but not quite, with the true geographical north and south poles. The law of attraction and repulsion explains why a freely suspended magnet will always point north and south.

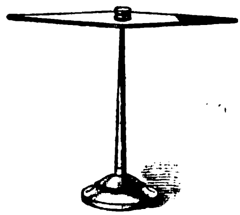


FIG. 4

It is impossible to produce a magnet with only one pole. If a long bar magnet is broken into any number of parts, as in Fig. 5, each part will still be a magnet and have two unlike poles.

6. Induced Magnetism.—Magnetism can be induced in a piece of unmagnetized iron by simply bringing a magnet near it. For example, if an unmagnetized bar of iron is laid on a sheet of paper, as in Fig. 6, iron filings sprinkled over it will show no tendency to cling to it, but if a

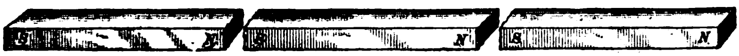


FIG. 5

horseshoe magnet is brought into the position indicated and the paper is gently tapped to jar the filings, they will cling to the ends of the bar as if it were a magnet. This is due to magnetism induced in the bar by the magnet.

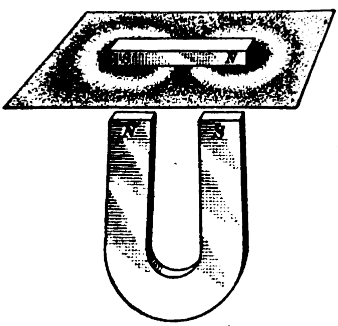


FIG. 6

Whenever a magnet is brought near iron, poles are induced in the iron adjacent to the poles of the magnet, but unlike them; a north pole is induced in the iron adjacent to the south pole of the magnet, and a south pole in the iron adjacent to the north pole of the magnet. Since unlike poles attract each other, the iron and the magnet show mutual attraction; that is, the iron is drawn toward the magnet and the magnet toward the iron.

7. Lines of Force and Magnetic Field.—Iron filings sprinkled on a sheet of cardboard laid over a bar magnet,

as shown in Fig. 7, will arrange themselves in lines that seem to issue from each pole in all directions and to curve until they enter the other pole. If the magnet is held endwise to the cardboard, the filings will arrange themselves as shown in Fig. 8. In both cases, gently tapping the cardboard will assist the filings to arrange themselves.

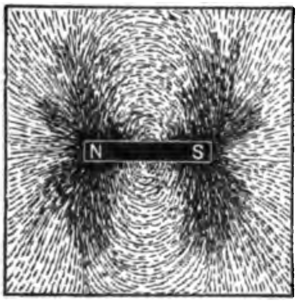


FIG. 7

8. The experiment illustrated in Fig. 9 also shows the action of magnetic force surrounding a magnet. A steel needle is magnetized by rubbing one end on one pole of a bar magnet and the other end on the other pole; the needle is then thrust through a cork so that the ends project, as at *n s*. The bar magnet is laid in the bottom of a glass or earthenware vessel (not metal), the vessel is partly filled with water and the cork is floated on the water so that one end of the needle will project toward a pole of the magnet without touching it.

If the cork does not move, this fact indicates that adjacent poles of the needle and bar are unlike. The cork should then be inverted so as to bring like poles near each other, when the needle and cork will promptly move in a curved path, approximately as indicated by the arrows, until near the other pole of the magnet. The shape of this path depends on the position in which the cork is placed relative to the magnet pole, being different when placed directly over the magnet than when placed so that the needle projects just beyond or at one side of the end of the bar.

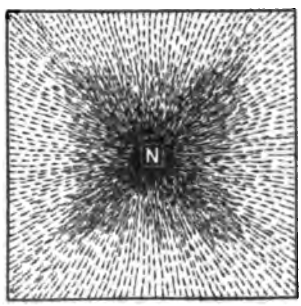


FIG. 8

9. By experiments such as those illustrated in Figs. 7, 8, and 9, magnetic forces are shown to act in the space surrounding a magnet along well-defined lines, called **lines of force.** The

word magnetism is frequently used in referring to all the lines of force collectively. These lines of force must not be conceived as invisible threads, but merely as directions in which the forces act. The space in which magnetic forces act around a magnet is called its **field.**

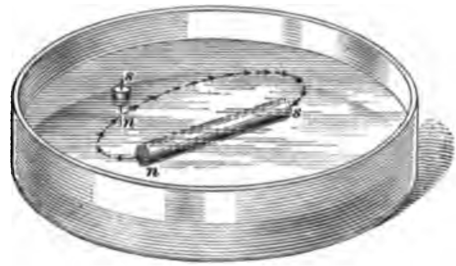


FIG. 9

Any magnetic substance, as iron or steel, in this field is influenced by the magnet and, in turn, influences the magnet. The strength of the field or the influence it can exert decreases as

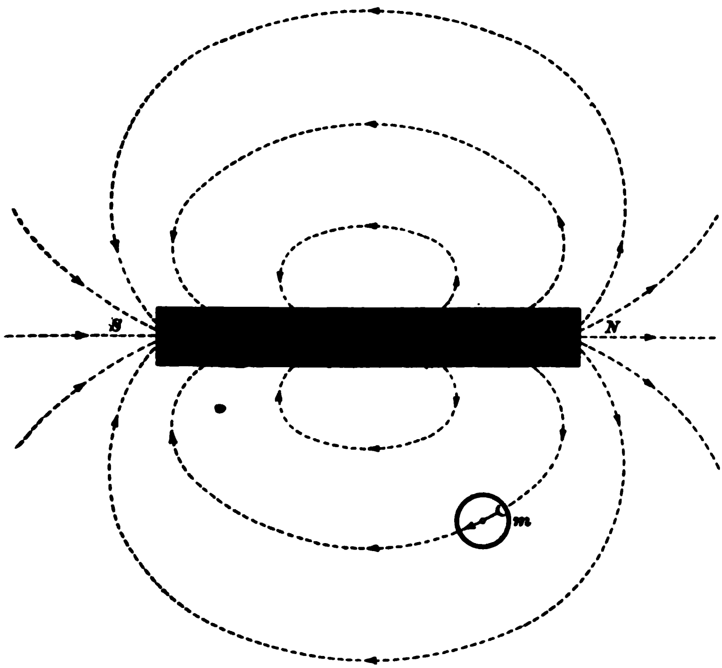


FIG. 10

the distance from the magnet increases. The total magnetism, or all the lines of force collectively, surrounding a magnet is

called the *flux* of the magnet, or the **magnetic flux.** The name *maxwell* has been adopted for one line of force, but it is not in universal use.

10. Direction of Lines of Force.—If a bar magnet is surrounded by air, the magnetic forces act in curved paths, connecting the poles, as indicated in Fig. 10, in which only a few lines of force are represented. The common assumption is that the forces act from a north pole and toward a south pole; that the lines of force pass out from the north pole, through the surrounding air, in at the south pole, and through the magnet to the north pole. This is called the *direction of the lines of force,* and the complete path is called the **magnetic circuit.**

11. The direction of lines of force in a magnetic field can be tested by means of a small, freely suspended magnet, as the

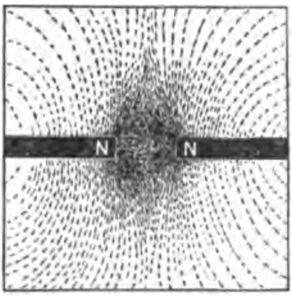


Fig. 11

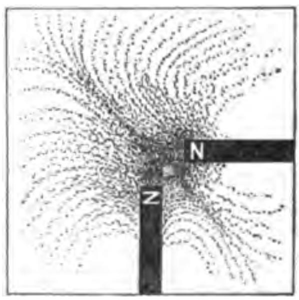


Fig. 12

needle of a compass. The needle always turns until the direction of the lines of force within its body coincides with the direction of the lines of force in the field, as at *m*, Fig. 10. The north pole of the needle always points in the direction of the lines of force. Lines of force are usually represented by dotted lines and their direction by arrowheads on the dotted lines.

12. Consequent Poles.—Iron filings on a piece of paper or cardboard over the like poles of two magnets will arrange themselves as in Figs. 11 and 12. The lines of force are thus shown to be distorted from their natural position and to be crowded into new positions, depending on the strengths of the

two poles, thus forming what are called *consequent poles*. The lines of force never cross one another, but always change direction to coincide with other lines of force in the same magnetic field.

13. Magnetic and Non-Magnetic Substances.—Substances or materials in which magnetism is easily established are called *magnetic*. Iron and steel are the most important magnetic materials; nearly all other materials offer high opposition to the establishment of magnetism and are called *non-magnetic*.

MAGNETIC CIRCUITS

14. A magnetic circuit may be *closed*, *compound*, or *non-magnetic*. It is **closed** when a complete path for the lines of force is provided through magnetic materials, as in Fig. 1; it is **compound** when the path includes both magnetic and non-magnetic materials, as is the case with a bar magnet; and it is **non-magnetic** when it includes no magnetic materials.

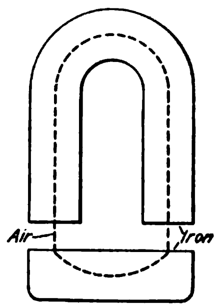


FIG. 13

15. The **length** of a magnetic circuit is the length of the average path of the lines of force. The length of a closed magnetic circuit can be easily approximated by measurement. In the case of a bar magnet, the length of the average path is hard to determine, for the lines spread widely in the part of the path through air. If the circuit is nearly all magnetic, as in Fig. 13, the average path will be approximately as indicated by the dotted line.

16. The **cross-section of a magnetic circuit** is a plane at right angles to the lines of force; it is the surface that would be formed by cutting squarely across the path of the lines of force. Such a section may be considered at any point in the circuit; if it is in a magnetic part, it is simply a section of the iron or steel of which the part is composed. For example, if a bar magnet were cut squarely in two, crosswise of its length,

either surface thus cut would be a section of the magnetic circuit at that point.

In short air gaps, as in Fig. 13, the lines of force do not spread much when leaving the iron, and a section of the magnetic circuit in the air gap is therefore approximately the same as through the adjacent iron. In longer air paths, as in Fig. 10, the lines of force spread widely and a section of the magnetic circuit is indefinite.

The area of a section, or the *sectional area*, is easily determined with reasonable accuracy in magnetic materials or in short air gaps, but it is difficult to determine in the longer paths through a non-magnetic substance. For example, if a bar magnet is 1 inch thick and 2 inches wide, the cross-sectional area of the magnetic circuit in the bar is 2 square inches.

17. The **magnetic flux density** in any section of a magnetic circuit is the number of lines of force, or maxwells, per unit area of the section. It may be expressed in lines of force per square inch or in maxwells per square centimeter. The unit *gauss*, meaning one line of force per square centimeter, is in some use, and density is sometimes expressed in gausses. The general custom in America, however, is to use lines of force per square inch or per square centimeter. Thus, 50,000 lines of force through a section of 2 square inches, or 12.9 square centimeters, is 25,000 lines per square inch, or approximately 3,876 lines per square centimeter.

18. The **reluctance** of a magnetic circuit is the opposition it offers to the passage of lines of force. Reluctance of a magnetic circuit may be likened to resistance of an electric circuit. Magnetic lines of force take the path of least reluctance, just as electricity seeks the path of least resistance. If the material of a magnetic circuit is homogeneous, or all of the same kind, the lines of force take the shortest possible path.

The reluctance of any magnetic circuit depends directly on its length and inversely on its sectional area; that is, the longer the circuit or the smaller its sectional area, the greater is its reluctance. The reluctance also depends on the materials of which the circuit is composed, being less for magnetic materials

than for non-magnetic materials, and less for some magnetic materials than for others.

19. The **unit of reluctance** most generally accepted is the **oersted.** For practical purposes, 1 oersted may be defined as the reluctance between opposite faces of a cube of any non-magnetic material 1 centimeter on each edge.

20. The **reluctivity** of any material is the reluctance between opposite faces of a cubical unit of it. The reluctivity of all non-magnetic materials is practically 1 oersted.

21. In all magnetic materials, the reluctance is greater at high densities than at low densities; but non-magnetic materials have very nearly the same reluctance at all densities. The density in a magnetic substance reaches *saturation point* when it is so high that the reluctance increases very much with a further slight increase of density. Good soft steel and iron will carry more than 100,000 lines of force per square inch before reaching the saturation point, while hard steel or cast iron will carry only about one-half as many.

22. The **permeance** of a substance is the reciprocal of its reluctance, and refers to the readiness with which the substance permits the establishment of magnetic lines of force. A substance that has low reluctance has high permeance. The permeance of a magnetic circuit may be likened to the conductance of an electric circuit.

The **unit of permeance** is the permeance of a cubic unit, usually 1 centimeter cube, of non-magnetic material. No name has been generally accepted for this unit.

23. The **permeability** of a substance is the reciprocal of its reluctivity, and is the permeance of a cubical unit of the substance. For practical purposes, the permeance of a centimeter cube of non-magnetic material is considered as 1, and the permeability of other materials is stated as a number indicating how much more permeable, or less reluctant, it is than non-magnetic materials. Thus, the permeability of some grades of iron is 2,000, because its reluctivity is one-two-thousandth that of air.

24. Magnetomotive force (abbreviated m. m. f.) is the force or influence that overcomes reluctance and establishes the flux of magnetism; it is analogous to electromotive force in an electric circuit.

25. Comparison of Electric and Magnetic Circuits. Electric and magnetic circuits have many analogous features; the names of some of these features appear opposite each other in the following list:

Electric Circuit	Magnetic Circuit
Electromotive force	Magnetomotive force
Electric current	Magnetic flux
Resistance	Reluctance
Conductance	Permeance

ELECTROMAGNETISM

MAGNETIC EFFECT OF ELECTRIC CURRENT

26. Every conductor carrying an electric current is surrounded by a magnetic field. This field has its maximum density in the space next to the body of a conductor, the density decreasing as the distance from the conductor increases. The magnetism thus established by electric current is called **electromagnetism.** It is no different from the magnetism of a permanent magnet, except in the method of establishing it.

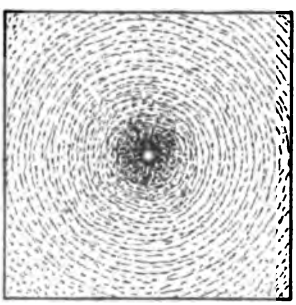


Fig. 14

If the conductor is threaded through a piece of cardboard and iron filings are sprinkled on the cardboard, they will arrange themselves in concentric circles around the conductor, as illustrated in Fig. 14. This effect will be observed throughout the entire length of the conductor; therefore, the field around any conductor carrying an electric current may be imagined as consisting of

magnetic whirls, that entirely surround the conductor, as shown in Fig. 15. The condition shown in Fig. 14 can be shown by experiment, but that shown in Fig. 15 is inferred from the other.

27. Direction of Lines of Force Surrounding an Electric Current.—If a conductor carrying electricity in the direction indicated by the long arrow, Fig. 16, is held over a magnetic needle, the needle will deflect as indicated by the curved arrows toward a position at right angles to the direction of the conductor. If the conductor is then held under the needle, the needle will reverse its direction. Fig. 17 shows the indications of two compass needles, one above and one below a conductor carrying electricity, showing that the direction of the lines of force must be as indicated by the curved arrows. These experiments show that *lines of force encircle an electric current clockwise* when looking in the direction of current. This statement is important and should be remembered. The word *clockwise* means in the direction of movement of the hands of a clock or a watch and is made clear in Fig. 17.

Fig. 15

28. In an actual experiment, the compass needles may not turn so nearly at right angles to the conductor as is indicated in Fig. 17, but they will approach the positions shown, their deflection depending on the strength of the current.

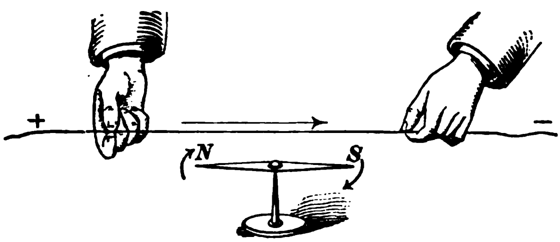


Fig. 16

Reversing the current will reverse the deflections of both needles, showing that the direction of the lines of force has reversed; but they still encircle the conductor clockwise to an observer facing the direction of the current.

29. The compass needle test can also be used to determine the direction of current in a conductor. If convenient, a portion of the conductor should be arranged in a north and south direction, parallel to the normal position of the needle. The compass should then be held near the conductor, and the

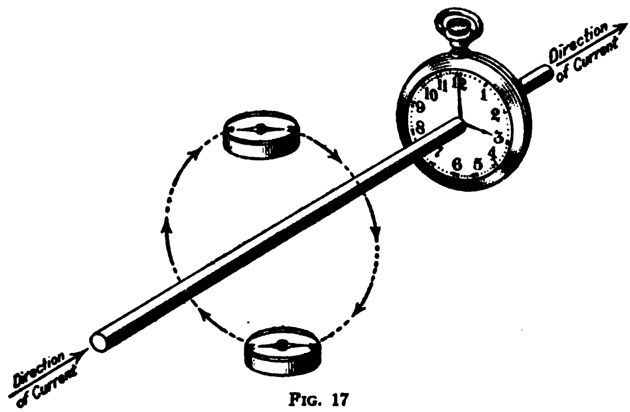
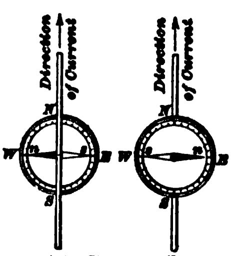


Fig. 17

needle will then indicate which way the magnetic flux encircles the conductor. If clockwise, looking along the conductor, the direction of current is from the observer; if counterclockwise, the direction of current is toward the observer. Fig. 18 (*a*) shows the compass under a conductor and (*b*) shows the compass above the same conductor, causing the needles to point in opposite directions; both positions indicate clockwise direction of flux looking north, showing that the direction of current must be north.



(*a*) Fig. 18 (*b*)

By looping the conductor over and under the needle, as in Fig. 19, the deflection can be much increased, since the flux surrounding both conductors tends to deflect the needle in the same direction. By looping the wire several times around the needle, that is, by forming a coil with the needle inside, the turning effect is still further increased, so that a very small current will produce a considerable deflection.

30. Mutual Influence of Parallel Currents.—If two or more parallel conductors are carrying current in the same direction, the magnetic flux surrounding them tends to draw them together. The lines of force around each conductor tend to unite with those of the other, forming magnetic flux that encircles both the conductors, as in Fig. 20 (*a*), or all of them if there are several; the tendency of the lines of force to traverse the shortest possible path makes them act like elastic bands drawing the conductors together.

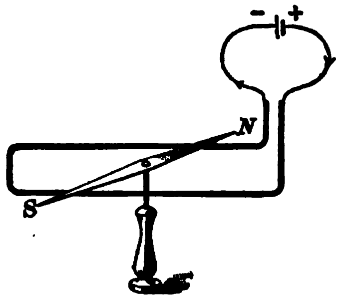
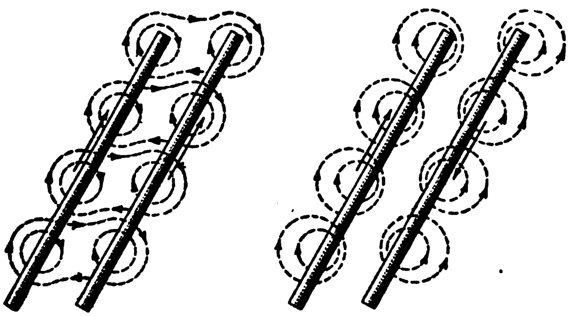


FIG. 19

Two parallel conductors carrying current in opposite directions are acted on by a force tending to separate them. The lines of force, being opposite in direction, cannot unite around the conductors, but



(*a*) FIG. 20 (*b*)

must all pass between them, as in Fig. 20 (*b*), thus tending to crowd them apart. In some electrical machines, the stresses caused in this way sometimes become enormous when the currents are large. In such machines the conductors must be fastened and braced very securely to hold them in place. For example, short circuits on large generators and transformers may work great injury by tearing the conductors out of place or crushing the insulation.

ELECTROMAGNETIC SOLENOID

GENERAL THEORY

31. If electricity flows in a conductor bent into a loop, as in Fig. 21, all the magnetic flux will pass through the loop in the same direction. With current in the direction indicated,

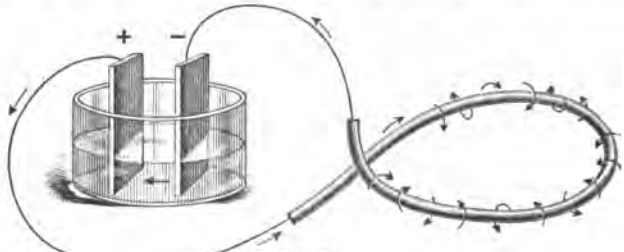


FIG. 21

the loop acts similarly to a bar magnet with the north pole downwards through the loop.

A conductor coiled into a helix, as in Fig. 22, is called a **solenoid**; with electricity flowing in the direction indicated by the arrows at the conductor ends, lines of force thread through the solenoid, the magnetic circuit being indicated by the arrows forming loops. A solenoid in which electricity is flowing is an **electromagnetic solenoid**, or a *solenoid magnet*, with poles and attractions and repulsions similar to those of a bar magnet; if suspended so as to turn freely, such a solenoid assumes a position with its axis (the line through the centers of its several turns) in a north-and-south direction. The circuit of such a magnet is wholly non-magnetic.

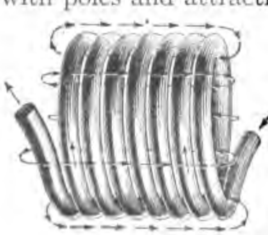


FIG. 22

32. The **polarity** of an electromagnetic solenoid can be determined, provided the direction of current is known, by the method illustrated in Fig. 17. That method applied to Fig. 22 shows that the lines of force

encircle the conductors in a direction to cause them to combine in paths indicated by the long loops, making the left end of the solenoid magnet a north pole and the right end a south pole. The polarity can also be tested by holding a compass needle or a bar magnet near the end of the solenoid, remembering, that unlike poles attract each other. Still another test is to suspend the solenoid so that it can swing freely to a north-and-south direction.

33. The direction of current in a solenoid magnet can be determined, when the polarity is known, as indicated in Fig. 23;

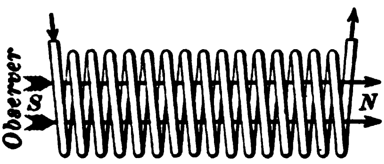


FIG. 23

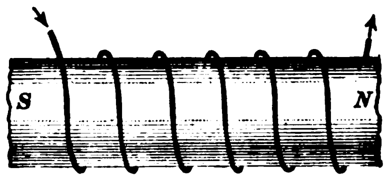


FIG. 24

namely, *the direction of current is clockwise when facing the south pole of the magnet.*

ELECTROMAGNETS

34. A solenoid magnet with a core of magnetic material is an **electromagnet.** Fig. 24 shows the essential principles; the core is usually made of highly permeable material, such as soft iron or steel. The solenoid is generally called either the *exciting coil* or the *magnetizing coil;* it is made of insulated wire so that the current will be confined to the intended path around the core, instead of escaping to the core itself.

35. Electromagnets are made in the *bar form* indicated in Fig. 24; in the *horseshoe form,* Fig. 25; in the *iron-clad form,* Fig. 26; and in various modifications of these forms. The form shown in Fig. 25 is provided with two cores M and a *yoke* b. The coils are wound on insulating spools and slipped over the cores; one coil c is shown in section. The iron-clad form, shown partly in section in Fig. 26, is provided with both an inner core M and an outer protecting shell S.

36. The presence of iron or steel in the magnetic circuit greatly reduces the reluctance of the circuit and increases the number of lines of force established by a given magnetomotive force; and the more nearly the magnetic circuit is closed through magnetic material the less is the reluctance. An electromagnet in the form shown in Fig. 25 is therefore lower in reluctance than one in the straight-bar form, Fig. 24; the iron-clad form, Fig. 26, can be made of less reluctance than either of the others, because its magnetic circuit is nearly all iron. The reluctance of the form shown in Fig. 25 could be decreased by the addition of an iron armature connecting the free ends of the two cores.

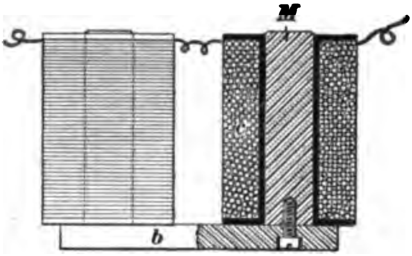


Fig. 25

37. The polarity of an electromagnet and the direction of current in its exciting coil can be determined by the methods previously described. For example, if the bar-type electromagnet, Fig. 24, is held so that the current encircles it clockwise, the end toward the observer is the south pole; or if the polarity is first determined by some other test, as with a compass, and the observer faces the south pole, the direction of the current is clockwise. When facing the poles of a horseshoe electromagnet, Fig. 25, the current must encircle one pole clockwise and the other counter-clockwise in order that one shall be a south pole and the other a north pole. This fact must be observed when connecting the coils of electromagnets.

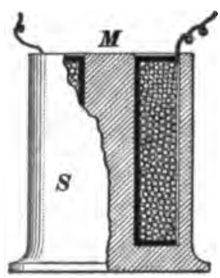


Fig. 26

38. Comparison of Permanent Magnets and Electromagnets.—Both permanent magnets and electromagnets have poles, magnetic fields, and similar attractions and repulsions. Permanent magnets are made of hardened steel, which cannot be magnetized to a very high degree but which holds its magnetism

for years. Electromagnet cores are made of soft iron or of steel, which can be magnetized to a very high degree while the magnetomotive force is applied, but which loses nearly all its magnetism as soon as current ceases in the magnetizing coil.

39. The magnetism retained by a magnet after the magnetomotive force ceases is called **residual magnetism.** By reversing the magnetomotive force, that is, by establishing a magnetomotive force of proper strength in the reverse direction, the residual magnetism can be removed, and the magnet is said to be **demagnetized.** The magnetomotive force necessary to demagnetize a magnet is a measure of its *coercive force*, or power of resisting magnetization or demagnetization. **Permanent magnetism** is residual magnetism in materials having high coercive force. The coercive force of magnet cores depends on the quality of iron or steel and especially on its degree of hardness. Both high permeability and low coercive force are desirable in electromagnet cores for most purposes, and these qualities are found in wrought iron and in soft steel.

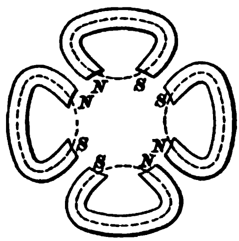


FIG. 27

Magnets can be demagnetized by subjecting them to rapidly reversing magnetomotive force and gradually decreasing this force. Watches in the pockets of those who operate electric machinery sometimes become *magnetized*, that is, some of the steel parts become permanent magnets, thereby injuring the time-keeping ability. This magnetism can be removed by suspending the watch at one end of a string, twisting the string tightly, holding the rapidly whirling watch near a strong magnet, and then gradually withdrawing it from the magnet while it is still whirling. All this is simply to reverse rapidly the magnetism and at the same time weaken it until entirely removed.

40. Generator and Motor Magnets.—The frames, pole pieces, and field coils of direct-current generators and motors form electromagnets. Fig. 27 shows four horseshoe permanent magnets, so placed as to approach very nearly the

form of magnet used in street-railway motors. The general shape of the magnetic circuit of each magnet is indicated by the dotted lines. In Fig. 28 the adjacent legs of these horseshoe magnets are merged together, but the dotted loops show that the four magnetic circuits are still complete in themselves. Fig. 29 is the outline of a section through the magnet frame of a street-railway motor. Four magnetizing coils are so connected that the path of the current is around adjacent poles in opposite directions, as can be seen by following the arrowheads on the full lines representing the wires encircling the poles. The poles are thus alternately north and south, the lines of force passing across between the poles, as indicated by the dotted lines with arrowheads, and completing their circuit by way of the magnet cores and the circular yoke inside which the poles are attached.

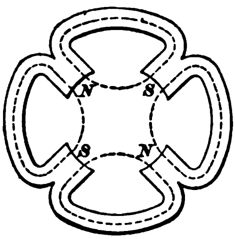


FIG. 28

41. Soft cast steel is extensively used for the magnet frames, or yokes, of generators and motors, because it is much cheaper than wrought-iron forgings of the intricate shapes required. Cast iron of high grade is also sometimes used for the same purpose, though inferior in permeability and of higher coercive force than soft cast steel. Cast-iron pole cores are seldom advisable because of the large cross-section required to carry the necessary flux; cast-steel poles are sometimes bolted to cast-iron frames.

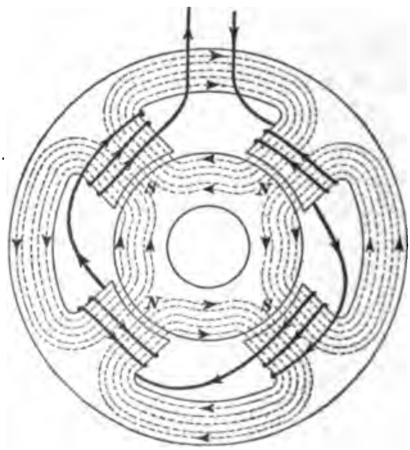


FIG. 29

Frame rings, or yokes, are also made by shearing strips from rolled-steel plate of the proper thickness, and then rolling and

electrically welding the strips into rings. Such yokes have the advantages of uniform structure, high permeability, small coercive force, and great strength. The pole pieces for such frames are usually made of thin plates punched from large soft-steel sheets and assembled and riveted together in the required form, and bolted inside the frame rings. Such pole pieces have uniform structure and afford the best possible magnetic conditions.

42. Units of Magnetomotive Force.—The magnetomotive force of electromagnets is generally expressed in **ampere-turns,** which are the product of the number of amperes and the number of turns in the exciting coil. For example, 10 amperes in a coil of 100 turns, or 100 amperes in a coil of 10 turns, or 5 amperes in a coil of 200 turns, all give the same magnetomotive force, namely, 1,000 ampere-turns. A coil of 500 turns having a resistance of 10 ohms, when connected across a 50-volt circuit, would give $\frac{50}{10}\times 500=2,500$ ampere-turns of magnetomotive force.

43. Magnetomotive force may also be expressed in **gilberts**; 1 gilbert is the magnetomotive force that will establish 1 line of force, or 1 maxwell, through a reluctance of 1 oersted. One ampere-turn equals 1.257 gilberts, or the number of gilberts equals 1.257 times the number of ampere-turns. Gilberts are much less used, especially in America, than ampere-turns.

44. The **magnetic intensity,** or *magnetizing force*, in a magnetic circuit is the magnetomotive force per unit length of circuit expressed in *ampere-turns per inch* or *gilberts per centimeter*.

EXAMPLE.—A coil of 100 turns and 5.5 ohms is connected across a 110-volt circuit and used to excite a magnetic circuit 6.28 inches long. What is the magnetizing force in: (*a*) ampere-turns per inch, and (*b*) gilberts per centimeter?

SOLUTION.—(*a*) The magnetomotive force in ampere-turns is $\frac{110}{5.5}\times 100$ $=2,000$, and the magnetizing force is $2,000\div 6.28=318.5$ ampere-turns per inch. Ans.

(*b*) The magnetomotive force in gilberts is $2,000\times 1.257=2,514$, and the length of the circuit in centimeters is $6.28\times 2.54=15.95$; therefore, the magnetizing force is $2,514\div 15.95=157.6$ gilberts per centimeter.

ELECTRIC CALCULATIONS

CROSS-SECTIONAL AREAS OF ELECTRIC CONDUCTORS

45. A **cross-section of a conductor** is the surface formed by cutting the conductor square across in a plane at right angles, or perpendicular, to its length. If a round, or cylindrical, conductor *a b*, Fig. 30, is cut squarely across, the end is a cross-section. If the conductor is solid, the cross-section is solid, as at *c*, view (*a*); if the conductor is tubular, the cross-section is hollow, as in view (*b*). A cross-section shows the shape of the conductor at the place where the section is taken. For example, if the section is a circle, as at *c*, the conductor *a b* is round wire either solid or tubular; if the section is a rectangle as at *f*, views (*c*) and (*d*), the conductor *d e* is a rectangular bar either in the form of a ribbon, or strip, as in (*c*), or a square, as in (*d*). Conductors in each of the forms shown are used.

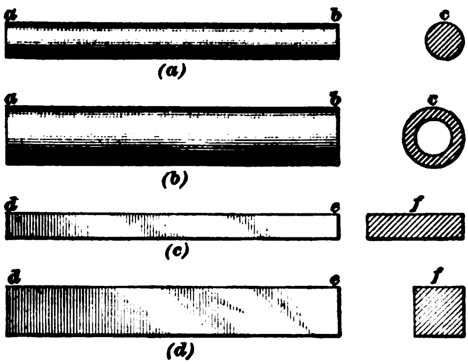


FIG. 30

46. The **mil** is a unit used to express dimensions of conductors and thickness of insulation. Thus, 1 mil = .001 inch; 1 inch = 1,000 mils; $\frac{1}{2}$ inch = 500 mils; 250 mils = $\frac{1}{4}$ inch; etc.

47. The **circular mil** (abbreviated c. m.) is a unit used to express sectional areas of conductors. The distance directly

through the center of a round conductor is the diameter of the conductor, as indicated at *d*, Fig. 31, and this diameter is the same in all directions. *The sectional area of any cylindrical conductor, in circular mils, is the square of its diameter in mils.* Thus, if a wire is 100 mils in diameter, its sectional area is $100 \times 100 = 10,000$ circular mils; a wire 1 inch, or 1,000 mils, in diameter has a sectional area of $1,000 \times 1,000 = 1,000,000$ circular mils.

48. The sectional areas of rectangular conductors are also expressed in circular mils. Fig. 31 shows, in dotted lines, a square circumscribed around a circle. The side of this square is the same as the diameter of the circle, and the area of the square in square mils is therefore the square of the diameter in mils. The square is evidently larger than the circle, the area of the circle being .7854 times the area of the square. Then, to determine the sectional area in circular mils of a rectangular conductor, find its sectional area in square mils and divide by .7854; that is,

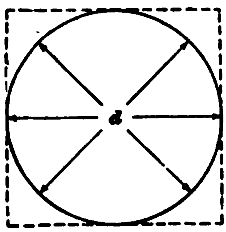


FIG. 31

$$circular\ mils = \frac{square\ mils}{.7854}$$

EXAMPLE 1.—Find the sectional area in circular mils of a ribbon-shaped conductor with a cross-section $\frac{1}{8}$ in. $\times \frac{3}{8}$ in.

SOLUTION.— $\frac{1}{8}$ in. = .125 in. = 125 mils; $\frac{3}{8}$ in. = .375 in. = 375 mils.

$$\text{Circular mils} = \frac{125 \times 375}{.7854} = 59,683. \quad \text{Ans.}$$

EXAMPLE 2.—Find the sectional area in circular mils of a conductor with a cross-section 1 inch square.

SOLUTION.— 1 in. = 1,000 mils.

$$\text{Circular mils} = \frac{1,000 \times 1,000}{.7854} = 1,273,237. \quad \text{Ans.}$$

49. On the other hand, it is sometimes necessary to calculate one dimension of a rectangular conductor when the other dimension and the sectional area in circular mils are known.

This is done by finding the sectional area in square mils and dividing it by the given dimension in mils. By transposing the equation of Art. 48,

$$\textit{square mils} = .7854 \times \textit{circular mils}$$

EXAMPLE—If a ribbon-shaped conductor must be 120 mils thick and must have a sectional area of approximately 46,000 circular mils, what must be the width of the section?

SOLUTION.—Square mils $= .7854 \times 46{,}000 = 36{,}128$, and $36{,}128 \div 120 = 301.07$ mils. Ans.

NOTE.—A section 120 mils by 300 mils, giving a sectional area of 45,837 circular mils, would probably be used in such a case.

EXAMPLES FOR PRACTICE

1. What is the sectional area in circular mils of a conductor with a rectangular cross-section 160 mils by 375 mils? Ans. 76,400, nearly

2. A ribbon-shaped conductor $\frac{1}{8}$ inch thick must have a sectional area of approximately 56,000 circular mils; what must be its width in mils? Ans. 351.8

NOTE.— 350 mils would probably be used, giving a sectional area of 55,704 circular mils.

3. What is the sectional area in circular mils of a wire $\frac{1}{8}$ inch in diameter? Ans. 15,625

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50. Wire Gauges.—A **wire gauge** is a tool for determining the diameters of wires. Wire sizes are ordinarily designated by numbers, known as *gauge numbers*, and in specifying a number the gauge referred to must also be specified. Table I gives wire gauges and gauge numbers in common use. The first five numbers, 6–0, 5–0, etc., are pronounced *six naught*, *five naught*, etc. and are often written with the number of naughts indicated, as *000000* instead of 6–0.

Wire for electrical conductors in the United States is nearly always specified by the *Brown & Sharpe gauge* (B. & S. G.); this gauge is also called the *American wire gauge* (A. W. G.). Each decrease of one in the gauge number designates a wire approximately 26 per cent. larger in sectional area, and each decrease of three gauge numbers designates a wire of approximately two times the sectional area. Thus, a No. 12 (B. & S.) wire is 26 per cent. larger than a No. 13 and No. 10 is twice as large as No. 13.

TABLE I
WIRE DATA

Gauge Number	Brown & Sharpe, or American, Gauge — Diameter Mils	Brown & Sharpe, or American, Gauge — Sectional Area Circular Mils	Roebling, or Washburn & Moens, Gauge — Diameter Mils	Roebling, or Washburn & Moens, Gauge — Breaking Stress (Steel)	Birmingham, or Stubs', Gauge — Diameter Mils	Gauge Number
6–0			462	16,619		6–0
5–0			431	14,522		5–0
4–0	460.0	211,600.00	394	12,130	454	4–0
3–0	409.6	167,800.00	363	10,292	425	3–0
2–0	364.8	133,100.00	331	8,605	380	2–0
0	324.9	105,500.00	307	7,402	340	0
1	289.3	83,690.00	283	6,290	300	1
2	257.6	66,370.00	263	5,433	284	2
3	229.4	52,630.00	244	4,676	259	3
4	204.3	41,740.00	225	3,976	238	4
5	181.9	33,100.00	207	3,365	220	5
6	162.0	26,250.00	192	2,895	203	6
7	144.3	20,820.00	177	2,461	180	7
8	128.5	16,510.00	162	2,061	165	8
9	114.4	13,090.00	148	1,720	148	9
10	101.9	10,380.00	135	1,431	134	10
11	90.7	8,234.00	120	1,131	120	11
12	80.8	6,530.00	105	866	109	12
13	72.0	5,178.00	92	665	95	13
14	64.1	4,107.00	80	503	83	14
15	57.1	3,257.00	72	407	72	15
16	50.8	2,583.00	63	312	65	16
17	45.3	2,048.00	54	229	58	17
18	40.3	1,624.00	47	174	49	18
19	35.9	1,288.00	41	132	42	19
20	32.0	1,022.00	35	96	35	20
21	28.5	810.10	32	80	32	21
22	25.3	642.40	29	62	28	22
23	22.6	609.50	26	49	25	23
24	20.1	404.00	23	42	22	24
25	17.9	320.40	20	31	20	25
26	15.9	254.10	18	25	18	26
27	14.2	201.50	17	23	16	27
28	12.6	159.80	16	20	14	28
29	11.3	126.70	15	18	13	29
30	10.0	100.50	14	15	12	30
31	8.9	79.70	13.5	14	10	31
32	8.0	63.21	13.0	13	9	32
33	7.1	50.13	11.0	9.5	8	33
34	6.3	39.75	10.0	7.9	7	34
35	5.6	31.52	9.5	7.1	5	35
36	5.0	25.00	9.0	6.4	4	36
37	4.5	19.83				
38	4.0	15.72				
39	3.5	12.47				
40	3.1	9.89				

Other wire gauges are the Roebling, or Washburn & Moens (W. & M.), and the Birmingham, or Stub's, (B. W. G.). The Roebling gauge is generally used to specify iron and steel wire. The Birmingham gauge is used to specify wire for other than electrical purposes, except iron and steel wire. As steel wire is used in electrical work more for tensile strength than as conductors, its breaking stress is given in the table.

RESISTANCE OF CONDUCTORS

51. The ohm is sometimes too small to express the value of resistance conveniently, and the **megohm,** which equals one million ohms, is then used. If the ohm is too large, the **microhm,** which equals one millionth part of an ohm, is used. The megohm is therefore a multiple of the ohm, and the microhm is a submultiple of it.

52. The **specific resistance,** or *resistivity*, of a material is the resistance between opposite faces of a cube of the material measuring 1 unit on each edge. Resistivity may be expressed for the centimeter cube or for the inch cube. In either case, the length of the path for which the resistance is expressed is 1 unit and its cross-section 1 unit square, that is, either 1 centimeter long by 1 square centimeter cross-section, or 1 inch long by 1 square inch cross-section. The resistivities given in Tables II and III are for such units.

53. Resistivities are also frequently expressed per **mil-foot,** a unit 1 circular mil in cross-sectional area and 1 foot long. For practical calculations, the resistivity of copper conductors at a temperature of 25° C. (77° F.) is considered 10.8 ohms per mil-foot.

54. Laws of Resistance.—The resistance of any material body changes according to the following laws:

1. Directly with the length.
2. Inversely with the sectional area; that is, directly with the reciprocal of the sectional area.
3. With the temperature, though not in direct proportion.

Thus, doubling the length without changing the sectional area or the temperature doubles the resistance; doubling the sectional area without changing the length or temperature

TABLE II

RESISTIVITIES OF CONDUCTORS

Material	Resistance, in Microhms, At 0° C. or 32° F.	
	Centimeter Cube	Inch Cube
Brass, commercial	7.200	2.840
Carbon, arc light	5,100 to 7,600	2,000 to 3,000
Copper, annealed	1.594	.627
Copper, hard drawn	1.620	.638
German-silver wire	20.900	8.240
Iron, wrought	13.800	5.450
Lead, compressed	19.500	7.680
Mercury, commercial	94.300	37.200
Platinum, annealed	8.980	3.540
Phosphor-bronze, commercial	8.480	3.340
Silver, annealed	1.490	.587
Silver, hard drawn	1.590	.626
Steel wire	13.500	5.320

halves the resistance; changing the temperature generally changes the resistance.

If the length, cross-sectional area, and resistivity of a conductor is known, its resistance can be calculated by the formula

$$R=\frac{r\,l}{a},$$

in which R = resistance;
r = resistivity;
l = length;
a = sectional area.

The formula gives the resistance R in the same units, microhms or ohms, as the resistivity r and at the same temperature as

that for which r is given. When using values of resistivity from Tables II and III, the length l must be in centimeters when r is for a centimeter cube, and in inches when r is for an inch cube. In calculating the resistance of conductors and using the constant 10.8 ohms per mil-foot, l must be in feet and a in circular mils.

TABLE III

RESISTIVITIES OF INSULATORS*

Material	Resistance, in Ohms, at Ordinary Atmospheric Temperature	
	Centimeter Cube	Inch Cube
Asbestos	160×10^9	630×10^8
Celluloid	71×10^9	28×10^9
Ebonite	28×10^{15}	11×10^{15}
Fiber, vulcanized, black	68×10^{12}	27×10^{12}
Fiber, vulcanized, red	10×10^{12}	4×10^{12}
Fiber, vulcanized, white	14×10^{12}	6×10^{12}
Glass, ordinary window	90×10^{12}	355×10^{11}
Glass, flint	20×10^{15}	8×10^{15}
Gutta percha	450×10^{12}	180×10^{12}
Marble	510×10^6	200×10^6
Mica	84×10^{12}	33×10^{12}
Paraffin oil	8×10^{12}	32×10^{11}
Paraffin, solid	33×10^{15}	13×10^{15}
Paper, ordinary	51×10^9	20×10^9
Porcelain	540×10^{15}	213×10^{15}
Shellac	9×10^{15}	35×10^{14}
Slate	78×10^9	31×10^9
Sterling varnish	205×10^{11}	8×10^{12}
Wood, dry, untreated	635×10^{12}	250×10^{12}
Wood, dry, paraffined	380×10^{13}	150×10^{13}
Wood, tarred	167×10^{13}	658×10^{12}

* These values are approximate; the resistivity varies greatly with purity and method of preparation.

EXAMPLE 1.—Find the resistance between opposite faces of a carbon block having the dimensions given in Fig. 32.

SOLUTION.—The resistivity of carbon, as given in Table II, is from 2,000 to 3,000 microhms per inch cube, and either of these values can be used for r in the formula. For present purposes, the average, 2,500, can be used. There are three paths to consider, as follows:

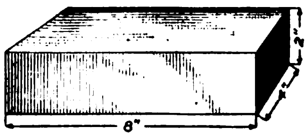


FIG. 32

1. $l_1 = 2$ in., $a_1 = 4 \times 8 = 32$ sq. in., and

$$R_1 = \frac{2{,}500 \times 2}{32} = 156\tfrac{1}{4} \text{ microhms. Ans.}$$

2. $l_2 = 4$ in., $a_2 = 2 \times 8 = 16$ sq. in., and

$$R_2 = \frac{2{,}500 \times 4}{16} = 625 \text{ microhms Ans.}$$

3. $l_3 = 8$ in., $a_3 = 2 \times 4 = 8$ sq. in., and

$$R_3 = \frac{2{,}500 \times 8}{8} = 2{,}500 \text{ microhms Ans.}$$

EXAMPLE 2.—Calculate the resistance of 2,000 feet of No. 6 (B. & S.) copper wire using a resistivity of 10.8 ohms per mil-foot.

SOLUTION.—The formula $R = \frac{r\,l}{a}$, in which $r = 10.8$, $l = 2{,}000$, and $a = 26{,}250$ circular mils (Table I), gives

$$R = \frac{10.8 \times 2{,}000}{26{,}250} = .823 \text{ ohms. Ans.}$$

55. The *effect of temperature change* on the resistance of conductors need be considered only when calculating sizes of conductors that will be subject to wide variations of temperature and where the resistance must be known with considerable accuracy. This is the case with many of the conductors in electric generators and motors.

The resistance of copper and of most other metals used for electric conductors increases approximately 1 per cent. for each 2.5° C., or 4.5° F., rise in temperature (more accurately, .42 per cent. for each degree centigrade). Thus, an increase of 25° C. will cause an increase of $25 \div 2.5 = 10$ per cent. in the resistance.

EXAMPLE 1.—If the resistance of a copper wire is .823 ohm at 25° C., what is its resistance at 60° C.?

SOLUTION.—The temperature rise is $60-25=35°$ C. and the resistance increase is $35\div 2.5=14$ per cent. The resistance at 60° C. is therefore $.823\times 1.14=.938$ ohm. Ans.

EXAMPLE 2.—Find the resistance of 500 feet of No. 14 (B. & S.) copper wire at: (*a*) 50° C.; (*b*) 80° C.

SOLUTION.—(*a*) The resistivity of copper at 25° C. is 10.8 ohms per mil-foot; 50° C. is an increase of 25° C. corresponding to $25\div 2.5=10$ per cent. increased resistance. The cross-sectional area of No. 14 wire (Table I) is 4,107 circular mils. By the formula,

$$R=\frac{r\,l}{a}=\frac{10.8\times 1.10\times 500}{4{,}107}=1.446 \text{ ohms. Ans.}$$

(*b*) At 80° C., an increase of 55° C., the resistance increase is $55\div 2.5=22$ per cent. greater than at 25° C. Therefore,

$$R=\frac{10.8\times 1.22\times 500}{4{,}107}=1.604 \text{ ohms. Ans.}$$

NOTE.—Although the results obtained in this way are not strictly accurate, they are close enough for general purposes, and the method is simple.

56. Specific Conductance, or Conductivity.—The conductance of a specified unit of a substance is called the *specific conductance*, or *conductivity* of the substance. Conductivity is the reciprocal of resistivity. The conductivity of commercial copper is often expressed as a percentage of the conductivity of pure annealed copper, known as *Matthiessen's standard;* thus the statement that copper has a conductivity of 98 per cent. means that its conductivity is .98 that of Matthiessen's standard.

EXAMPLES FOR PRACTICE

1. Calculate the resistance of 1,000 feet of No. 10 (B. & S.) annealed copper wire at: (*a*) 25° C.; (*b*) 80° C. Ans. { (*a*) 1.04 ohms, approx. (*b*) 1.27 ohms, nearly

2. Calculate the resistance of 5,000 feet of No. 12 (B. & S.) annealed copper wire at 60° C. Ans. 9.427 ohms, approx.

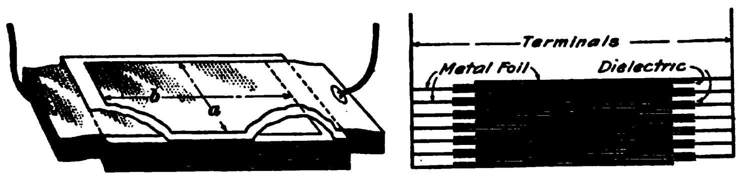
3. Calculate the resistance of 5 miles of No. 0 (B. & S.) annealed copper wire at 25° C. Ans. 2.7 ohms, approx.

DIELECTRIC CIRCUITS

ELECTRIC CONDENSERS

57. Any electric circuit that includes a condenser is a **dielectric circuit.** Practically all electric circuits are therefore also dielectric circuits, for a condenser is formed whenever two conductors are separated by an insulating substance. Condenser effect is sometimes present where undesirable in circuits and at other times is a desirable addition to a circuit. Commercial condensers are made in several forms for use where needed.

58. Plate condensers are made by assembling sheets of conducting element and insulation so that the insulation separates the conductors. The conductors are joined electrically in



(a) FIG. 33 (b)

two groups, alternate sheets in each group, and a terminal is connected with each group. Fig. 33 shows one method of constructing such a condenser, (*a*) being a general view with one conducting plate and one insulating sheet partly cut away, and (*b*), a diagrammatic cross-section. Tin-foil is generally used for the conductors, though any other metal in thin sheets can be used. Sheets of mica or oiled paper generally form the insulating material, or dielectric. The active parts of the condenser plates are those separated by dielectric, as indicated by the dimension lines *a b*. The product of these two dimensions and the number of sheets of dielectric is the *effective area*

of the dielectric. The complete condenser made as indicated is enclosed between insulating sheets that are firmly pressed together and securely clamped.

59. The **Leyden jar** is a form of condenser that is cheaply constructed and very effective for some purposes. A glass jar free from cracks and flaws is coated inside and outside with metal foil for possibly two-thirds of its height, as indicated at a, Fig. 34. A metal rod fitted in the cork extends toward the bottom and carries a piece of chain, some of which rests on the bottom in contact with the inner coating of metal. The end of the rod thus constitutes one terminal, and the outer coating the other; contact is made with the outer coating in any convenient way.

Fig. 34

60. The **electrostatic capacity,** or ***permittance***, of a condenser is the ratio between its charge and the electromotive force across its terminals. Its charge is the quantity of electricity that will flow into it with a given electromotive force. The units of capacity are the **farad** and the **microfarad**; the farad is the ratio between charge in coulombs and electromotive force in volts. In making calculations, capacity must always be considered in farads, but the capacities of condensers are practically always stated in microfarads. A microfarad is 1 millionth of a farad, or 1,000,000 microfarads = 1 farad. In practice, condenser capacities rarely exceed a very few microfarads.

Let C = capacity of condenser, in farads;
Q = quantity of electricity, or charge, in coulombs;
E = electromotive force, in volts, across condenser terminals.

Then,
$$C = \frac{Q}{E}$$

Example 1.—If an electromotive force of 10 volts establishes a charging current of 1 milliampere for .01 second in a condenser, what is the capacity of the condenser?

SOLUTION.—As coulombs = amperes × seconds and 1 milliampere = .001 ampere, the charge, in coulombs, is .001 × .01 = .00001. By the formula, the capacity

$$C = \frac{.00001}{10} = .000001 \text{ farad} = 1 \text{ microfarad. Ans.}$$

EXAMPLE 2.—How many coulombs of electricity will it require to charge a 2.5-microfarad condenser from a 50-volt circuit?

SOLUTION.— 2.5 microfarads = .0000025 farad = $\frac{Q}{50}$;

$Q = 50 \times .0000025 = .000125$ coulomb. Ans.

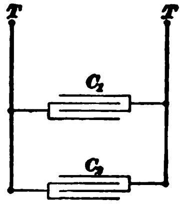


FIG. 35

61. Connections of Condensers.—In diagrams, condensers are usually represented by symbols as at C_1, C_2, Fig. 35. When they are connected in parallel, as shown, their combined capacity is equal to the sum of their individual capacities. For example, if C_1 and C_2 are the individual capacities of the two condensers between the terminals T, the combined capacity between these two terminals is

$$C = C_1 + C_2$$

The capacities of condensers in parallel are thus added similarly to the conductances of electric circuits in parallel.

62. When condensers are connected in series, as in Fig. 36, their combined capacity is found by adding the reciprocals of the capacities and taking the reciprocal of this sum. Thus,

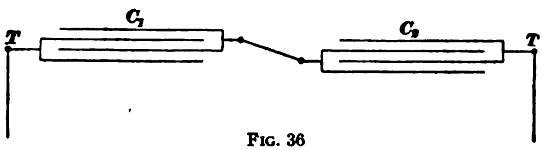


FIG. 36

if two condensers having capacities C_1 and C_2, are in series, the total capacity between the terminals T is

$$C = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}}$$

EXAMPLE.—Find the combined capacity of three condensers having capacities of 2, 3, and 4 microfarads connected in: (*a*) parallel; (*b*) series.

SOLUTION.—

(*a*) $C=2+3+4=9$ microfarads. Ans.

(*b*) $C=\frac{1}{\frac{1}{2}+\frac{1}{3}+\frac{1}{4}}=\frac{1}{\frac{13}{12}}=\frac{12}{13}=.92$ microfarad. Ans.

63. Condensers connected in parallel are subjected to the same voltage, as appears in Fig. 35. The voltages at the terminals of condensers connected in series are inversely proportional to the capacities of the condensers; the condenser with greatest capacity is subjected to the least voltage. If a high-voltage conductor is separated from earth by a series of insulators with intervening conductors, the weakest insulator may thus be subjected to the highest voltage with danger of break-down.

DIELECTRIC STRENGTH

64. The **dielectric strength of an insulating substance** is the maximum voltage that it can withstand without breaking down or being punctured. A puncture, or disruption, occurs when an electric spark passes through the insulation and thus forms a conducting path through it. A substance may show high resistance to low-voltage current, but may break down easily when high voltage is applied; another substance with comparatively low resistance may show much better ability to withstand puncture by high voltage. As soon as a puncture occurs the material is carbonized, or burned, around the puncture, thus practically destroying its insulating qualities, since carbon is a fairly good conductor. Insulating oils are an exception to this rule, because fresh oil immediately fills the openings caused by punctures, and the lighter carbonized particles rise to the surface.

65. The dielectric strength of a substance is determined by placing a sample between two electrodes and then gradually raising the voltage until the substance breaks down. The voltage that causes this breakdown is the dielectric strength of the material. This voltage divided by the thickness of the material tested gives the dielectric strength per unit thickness, a value by which the merits of different insulating materials

can be compared. The dieletric strength per unit is somewhat less in thick samples than in thin samples, probably because of the less uniform structure in the thick samples. Table IV will prove serviceable in selecting some of the more common insulating materials. The dielectric strength of any of these materials of any given thickness can be found approximately

TABLE IV

APPROXIMATE PUNCTURING VOLTAGES PER MIL

Material	Volts Per Mil	Material	Volts Per Mil
Asbestos	100	Leatheroid	125 to 300
Calico, treated with rubber	40	Linen cloth	125 to 200
Cambric, oiled	430	Linen, varnished	250
Canvas, oiled	125	Marble	165
Cotton cloth	90	Mica	430 to 700
Ebonite	725	Oiled cloth	450 to 600
Empire cloth	200	Paper, manila	125
Empire cloth, oiled	250	Paper, red rope	240
Fullerboard	400	Para rubber	450
Fiber	60	Paraffin	300
Glass, ordinary	200	Porcelain	230
Glass, lead	140	Porcelain (Locke)	415
Gutta percha	450	Presspahn	100 to 250
Hard rubber	250 to 950	Rosin	280
Jute, impregnated	20	Vulcabeston	60 to 100
Lava	75 to 250	Wax	280

by multiplying the thickness in mils by the puncturing voltage given in the table. Some reduction should be made for thicknesses above, say, 100 mils. On account of wide variations of test results, only approximate values can be given. Some of the materials named in the table are compositions of other materials and are known by trade names, such as presspahn and vulcabeston.

66. The **dielectric strength of air** appears higher with direct voltage than with alternating (rapidly reversing) voltage. It is also higher if the air is compressed than if at ordinary pressure or rarefied. Higher voltage is required to cause a

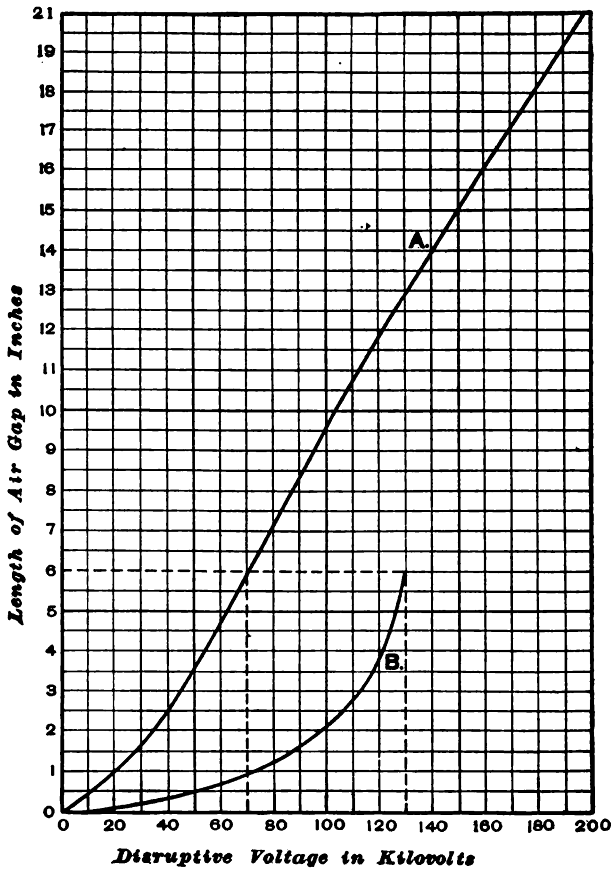


FIG. 37

spark through air between parallel disks than between needle points. Fig. 37 shows the dielectric strength of dry air at ordinary pressure with alternating voltage. Curve *A* is for sharp needle points, and curve *B* for polished brass balls $\frac{7}{8}$ inch in diameter. The disruptive, or puncturing, electromotive

force is given in kilovolts, the prefix *kilo* meaning 1,000. Dotted lines show the method of reading the curve to find the voltage that will cause a 6-inch spark; 70,000 volts are required between needle points and 130,000 between the brass balls. Voltages for other spark gaps are found in the same way.

EXAMPLES FOR PRACTICE

1. The capacities of four condensers in microfarads are, respectively, .5, 1, 4, and 6. Find their combined capacity when connected in: (*a*) series; (*b*) parallel.

Ans. { (*a*) .293 microfarad; (*b*) 11.5 microfarads

2. What is the combined capacity of five condensers of 2 microfarads each when connected in: (*a*) parallel? (*b*) series?

Ans. { (*a*) 10 microfarads; (*b*) .4 microfarad

3. What per cent. is added to the insulating quality of empire cloth by oiling it? Ans. 25

THEORY OF DIRECT-CURRENT GENERATORS AND MOTORS

ELECTROMAGNETIC INDUCTION

FUNDAMENTAL PRINCIPLES

1. Electromagnetic induction, broadly considered, relates to the electromotive force generated in a conductor within a magnetic field by relative cutting motion between the conductor and the flux of the field. The conductor may move and the flux remain constant in position, or the flux may move and the conductor be stationary. In either case, if the conductor cuts across the flux or is cut by it, an electromotive force is generated, and if the conductor forms a part of a complete circuit, a current is established throughout the circuit.

The electromotive force for nearly all commercial lighting and power circuits is furnished by a machine called a *generator*, the action of which is based on the principles of electromagnetic induction.

2. Electromagnetic induction may for convenience be classified as *transformer action* and *generator action;* but both actions are closely related and probably identical.

In **transformer action,** both the conductor that bears the exciting magnetomotive force and that in which the electromotive force is generated are stationary, and the electromotive force is induced by causing such motion of the flux of the exciting conductor as to cut across the conductor in which the

electromotive force is established. A movement of the flux may be set up by increasing or decreasing the exciting current or by changing the reluctance of the path of the exciting flux. The operation of a device called a *transformer* is based on the variation of the exciting current.

In **generator action** also, two sets of conductors are usually employed, one in which the magnetizing current is carried and the other in which electromotive force is generated. Either set of conductors is made movable while the other is stationary.

3. The *direction of motion of a flux* refers to the movement of the flux considered as a group of lines of force; for example, when a current in a wire increases, the flux moves outwards from the wire in the form of constantly expanding circles. The *direction of the flux* refers to the direction of the individual lines of force composing the flux; for example, the direction of the flux may be clockwise or counter-clockwise around the wire.

In order to generate an electromotive force, it is essential that there be a relative cutting motion between the flux and the conductor. No electromotive force will be generated if both the flux and the conductor are stationary, or if the motion of the conductor or the flux is such that the conductor does not cut across the flux or the flux cut across the conductor.

DIRECTION OF THE ELECTROMOTIVE FORCE

4. Generator Action.—The conductor $a\,b$, Fig. 1 (a), is moved toward the right across the magnetic flux of the permanent magnet, as indicated by the full-line, horizontal arrow. The direction of the inducing flux is downwards, as shown by the arrowheads on the dotted vertical lines. An electromotive force is set up in the conductor in such a direction that the current established will always produce a conductor flux that agrees in direction with the inducing flux on the side of the conductor that first comes in contact with the inducing flux and is opposite in direction on the other side of the conductor. This fact holds true whether the conductor or the

flux is the moving element. The direction of the conductor flux is indicated by the arrowheads on the curved lines surrounding *a b*. The direction of the electromotive force, as well as that of the current in this case, is from *a* to *b*, as indicated by the arrowheads on the circuit wires. The flux is more dense ahead of the conductor than behind it because of the relation between

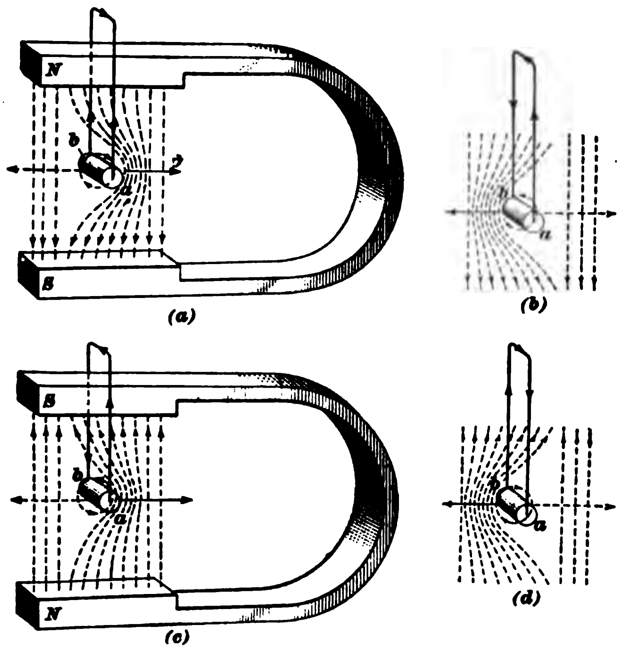


Fig. 1

the direction of the inducing flux and that of the conductor flux.

The direction of the induced electromotive force in any case where the relative direction of the movement of the flux and of the conductor is known may be determined by considering which side of the conductors has the denser flux. The direction of the circular conductor flux on that side agrees with the direction of the inducing flux, and the direction of the induced electromotive force is determined from the relation of the conductor current and its flux, as is explained in *Electricity and Magnetism*, Part 2.

The conductor $a\,b$, Fig. 1 (*b*), is moved toward the left and the induced electromotive force is from *b* to *a*. In (*c*), a conductor is represented as moving to the right in a field in which the direction of the flux is vertically upwards. The direction of the induced electromotive force is from *b* to *a*. In (*d*), the conductor is moved toward the left in the same field, and the direction of the induced electromotive force is from *a* to *b*.

It should be noted that when either the direction of the motion of the conductor or the direction of the flux is reversed, the direction of the electromotive force is reversed, as in Fig. 1 (*a*) and (*b*) or in (*a*) and (*c*); but, when both the direction of the flux and the direction of the motion of the conductor are reversed, the direction of the induced electromotive force remains unchanged, as in Fig. 1 (*a*) and (*d*) or in (*b*) and (*c*).

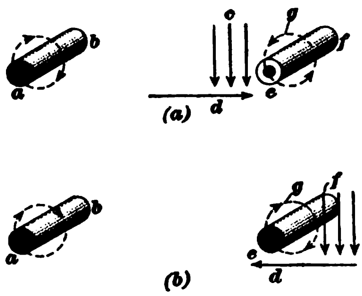


FIG. 2

5. Transformer Action. Fig. 2 (*a*) represents a stationary conductor $a\,b$ in which electricity is just starting to flow from *a* to *b*, or away from the observer, as indicated by the full black circle at the end of the conductor. The flux surrounding this conductor is therefore clockwise, and as a portion *c* of it expands in the direction of the arrow *d* lines of force of *c* move across a neighboring stationary conductor $e\,f$. The direction of the induced electromotive force in conductor $e\,f$ is from *f* to *e*, as determined from the relation of the moving flux *c* and the induced flux *g* of conductor $e\,f$. If $e\,f$ is part of a complete circuit, the current established is toward the observer, as indicated by the dot at the end of the conductor.

Consider the case when the current in conductor $a\,b$, view (*b*), has reached a steady value and is then decreased either by opening the circuit of the conductor or by increasing the resistance of the circuit. The flux *c* is now contracting toward

conductor *a b*, as indicated by arrow *d*. The induced electromotive force and the current in conductor *e f* are from *e* to *f*, or away from the observer, as indicated by the full black circle at the end of the conductor.

It should be noted that increasing the current in a conductor induces an electromotive force in the opposite direction in neighboring parallel conductors, and decreasing the current induces an electromotive force in the same direction.

SELF-INDUCTION

6. Suppose that conductors *a b* and *e f*, Fig. 2, are parts of adjacent turns of wire on the same side of a coil, Fig. 3 (*a*). The circuit of the coil is completed by a battery and a small key switch. When electricity starts to flow, the induced electromotive force of conductor *e f*, in the direction indicated by arrow *h*, opposes the impressed electromotive force, the direction of which is indicated by arrow *i*, in forcing current through the circuit. The value of the induced electromotive force depends on the rate at which lines of force cut across the conductor. As the rapidity of this cutting action is maximum at first and decreases as the current becomes steady, the opposing electromotive force decreases in value and becomes zero when the current becomes steady, because there is then no movement of the inducing flux.

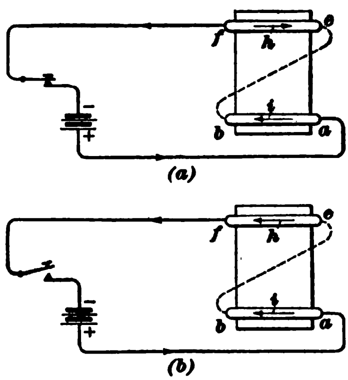


FIG. 3

When the key switch is opened, the current decreases and the direction of the induced electromotive force, as indicated by *h*, Fig. 3 (*b*), agrees with the direction in which electricity was flowing as indicated by *i*, thus tending to prolong the flow, possibly through a spark between the switch contacts.

When the coil in which the electromotive force is induced forms a part of the circuit carrying the inducing current, the electromotive force is self-induced, and is known as the **electromotive force of self-induction.**

7. Self-induction in a circuit always tends to retard any change, either of increase or decrease, in the existing current in the circuit. Circuits containing coils of wire wound on an iron core have comparatively large *inductance;* that is, a change of current causes a considerable electromotive force of self-induction. A single straight conductor without iron near it has small inductance; that is, a change of current induces only a small electromotive force of self-induction, and this is caused by the expanding or contracting flux cutting across a portion of the conductor itself.

A variable current in a circuit in which a considerable electromotive force of self-induction is generated, does not immediately rise or fall to a value indicated by an application of Ohm's law, but takes an appreciable time to arrive at such a value.

MUTUAL INDUCTION

8. When two conductors forming parts of separate circuits are so arranged that variable currents in each cause fluxes to cut across the other, the electromotive forces thus generated in each conductor are said to be due to **mutual induction.**

9. In Fig. 4, conductor $a\,b$ forms a part of a turn that has in circuit a battery and switch. The current is known as the *primary circuit.* Conductor $e\,f$ forms a part of a turn in a closed circuit, in which an electromotive force is generated by the action of the primary current. This circuit is known as the *secondary circuit.*

In Fig. 4 (a), the current is increasing in the primary circuit. In Figs. 3 (a) and 4 (a), arrows h and i have the same direction. The direction of the flux within the iron core, due to the current in conductor $a\,b$, Fig 4 (a), is indicated by arrow j; that of the flux within the iron core, due to the current in conductor $e\,f$, by arrow k—opposite in direction to arrow j.

When the primary current is increasing, the secondary flux tends to oppose the building up of the primary flux. The self-induction of the primary circuit is decreased because the rate at which lines of force of the primary flux cut across the active conductors of the primary circuit is lessened.

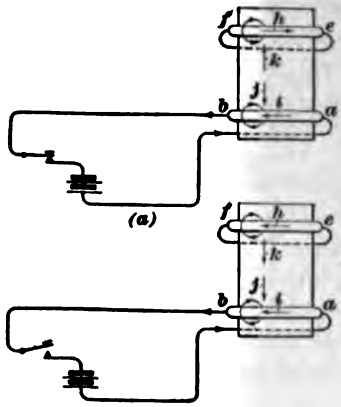


FIG. 4

When the current in the primary is decreasing, Fig. 4 (*b*), arrows *h* and *i* are in the directions indicated in Figs. 3 (*b*) and 4 (*b*), and the primary and the secondary flux within the core agree in direction, as indicated by arrows *j* and *k*. The primary flux is decreasing in density, owing to the decreasing primary current, and the secondary flux tends to oppose the rapidity of the decrease in density, thus lessening the electromotive force of self-induction of the primary coil.

The effect of mutual induction is therefore to neutralize some of the effect of self-induction, allowing changes of current to occur more promptly than in circuits in which only self-induction is present.

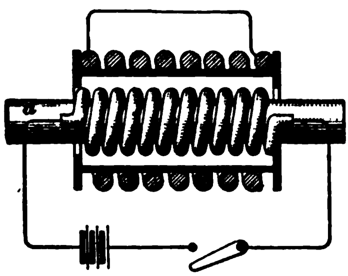


FIG. 5

10. The principles of mutual induction are utilized in induction coils and transformers. Fig. 5 shows a simple form of induction coil: The magnetic core is shown at *a*; the *exciting coil*, also called the *primary coil*, is wound on the core; and the coil in which the induced electromotive force is established, called the *secondary coil*, is wound outside the primary coil. There is no electrical connection between these coils. Any change in the current of the primary coil, such as that due

to opening or closing the circuit, causes a movement of the flux due to the varying magnetomotive force of the primary coil, and this flux in expanding or contracting induces an electromotive force in the turns of wire of the secondary coil. The action of the flux due to the varying magnetomotive force of the secondary coil is to decrease the effect of self-induction of the primary circuit

11. If a source of alternating electromotive force is substituted for the battery and switches, Fig. 5, alternating current will be set up in the primary coil and an alternating flux in the core; also, in the secondary coil, there will be generated by mutual induction an alternating electromotive force that will establish an alternating current in the secondary circuit. Such an arrangement of coils and a core form a device known as a *transformer*.

NON-INDUCTIVE CIRCUIT

12. The principle of mutual induction is frequently employed to make a circuit practically non-inductive. When the two wires of an alternating-current circuit are to be installed in iron tubes, called *conduits*, both wires are placed in the same conduit, but they are carefully insulated from each other and from the conduit. At any instant, the current in one wire is opposite to that in the other wire, because while one is acting as the incoming wire the other is acting as the outgoing wire of the same circuit. The effect of mutual induction between the two conductors practically neutralizes the effect of self-induction.

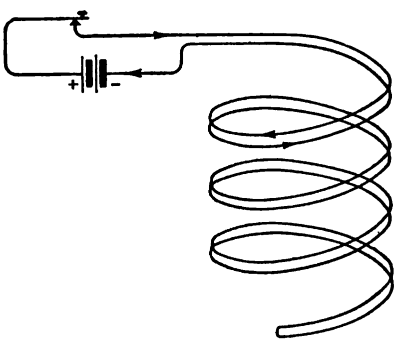


FIG. 6

When winding a resistance coil for a certain type of measuring instrument, the wire is doubled on itself and wound in such a

manner that the currents in adjacent conductors at any instant are in opposite directions.

Fig. 6 illustrates one method of winding coils so that their inductance is very small. The effect of mutual induction between the two conductors practically neutralizes the effect of self-induction, thus making the circuit nearly non-inductive, and allowing the current to build up to normal value quickly.

THE ELECTRIC GENERATOR

ELEMENTARY THEORY

13. An **electric generator** is a machine for converting mechanical energy into electrical energy by the application of the principles of electromagnetic induction. The moving element of the generator is usually driven by a steam engine, a gas engine, or a waterwheel, which causes relative motion between a magnetic flux and a group of conductors. An electromotive force is generated in the conductors, and if the circuit external to the generator is complete a current is established throughout the circuit.

A distortion of the magnetic flux occurs near each conductor, as indicated in Fig. 1. Lines of force that have been distorted tend to resume their original position and in so doing endeavor to move the body that causes the distortion in a direction opposite that of the movement required to set up the electromotive force. For instance, the magnetic forces acting on $a\,b$, Fig. 1 (a), tend to move it toward the left, and force must be applied to move the conductor toward the right. It is therefore necessary that force be applied continuously by the engine in order that the relative motion of flux and conductor in the generator be maintained.

14. An electric generator consists, in general, of an electromagnet for providing a magnetic flux; a device on which are mounted the conductors that cut across the flux or are cut by it; and a device for connecting the conductors to the external circuit.

The conductors on generators for direct-current service are mounted on the rotating element, called the *armature*, and connected to the external circuit by a current-rectifying device, called a *commutator*.

Generators for alternating-current service, called *alternators*, may have the conductors mounted on either the rotating element, called the *rotor*, or on the stationary element, called the *stator*.

When electrical connection is necessary with the conductors on the rotating element, it is usually made by means of metal rings, called *collector rings*, or *slip rings*, mounted on the rotor and sliding under stationary brushes.

15. Simple Form of Alternating-Current Generator. In direct-current generators of the usual type, alternating

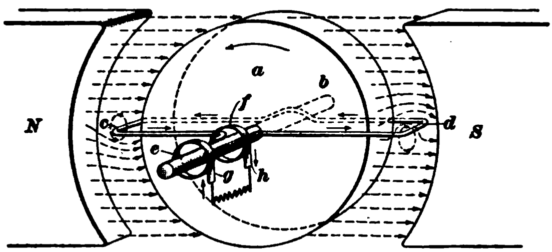


FIG. 7

electromotive forces are generated in the armature conductors and changed by the action of the commutator to direct current for the external circuit.

Fig. 7 shows an elementary type of alternating-current generator. A soft-iron armature core *a* on a shaft *b* carries on its convex surface conductors at *c* and *d* and revolves between magnetic poles *N* and *S* so that the conductors cut the flux of the magnetic poles. Electromotive forces are generated in these *active conductors*, which are connected by other conductors to the slip rings *e* and *f*. Stationary brushes *g* and *h*, which bear on the rings, serve to connect the armature conductors with an external circuit.

With a counter-clockwise direction of armature rotation and the flux in the direction indicated, the electromotive force

in *c* is toward the front, and in *d* toward the rear of the armature. The principles of electromagnetic induction, as explained in connection with Fig. 1, should be applied to the conditions of Fig. 7. The two conductors are so connected across the back of the armature that the two electromotive forces act in series to force current through the circuit.

16. The value of the electromotive force generated in a conductor is directly proportional to the rate at which it cuts across lines of force. If either the density of the flux or the speed of rotation of the armature is increased, a higher value of electromotive force is generated. A conductor when midway in the space between the tips of the pole pieces is moving parallel to the lines of force, and, therefore, as no lines are cut, the electromotive force will be zero. When conductor *c*, Fig. 7, is at its highest point, its electromotive force is zero. As it moves toward a position near the middle of the pole piece, it will cut across more and more lines of force for a given distance of circular movement until, at the position of *c* shown, maximum electromotive force is generated. In the next quarter revolution, the conductor cuts across a lessening number of lines of force for a given circular movement; therefore, the value of the electromotive force generated decreases and becomes zero when the conductor is at its lowest position and is moving parallel to the lines. When conductor *c* changes from cutting down to cutting up across the flux, the direction of the induced electromotive force changes, because the relative direction of motion of conductor and flux has been reversed. The electromotive force then increases until conductor *c* is in the position shown occupied by *d*, where maximum electromotive force is generated. For the remaining quarter revolution, the electromotive force decreases and becomes zero when conductor *c* again reaches its highest point.

With the one-turn armature of the simple alternator shown, the current in the whole circuit varies in value and changes in direction practically in unison with the changes in the generated electromotive force. The arrows near the brushes, Fig. 7, indicate the direction of the current in the external circuit

only when conductor *c* is moving downwards and conductor *d* upwards, as indicated. The current in the whole circuit is reversed in direction as the conductors *c* and *d* move through their upper and lower positions.

17. Alternating-Current Curve.—The rise and fall of the alternating current established by the simple generator shown in Fig. 7 is indicated by the curve shown in Fig. 8. The distances of the curve above or below the line *a b* represent increasing or decreasing values of electromotive forces and the distance along the horizontal line indicates intervals of time. The part of the curve above the line *a b* indicates a flow of electricity in one direction, called *positive*, through the circuit, and the portion below the line, a flow in the other direction, called *negative*.

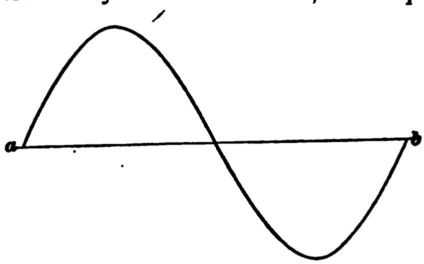


FIG. 8

18. Elementary Direct-Current Generator.—The machine shown in Fig. 7 may be changed to an elementary generator for providing direct current to an external circuit by the substitution of a commutator for the slip rings, as indicated in Fig. 9. The action of a commutator is called *commutation*.

The simple commutator shown consists of two semicircular bars *e* and *f* mounted near, but not touching, each other on the shaft *b* and insulated from it. Conductor *c* is connected to bar *e* and conductor *d* to bar *f*. The brushes *g* and *h* serve to connect the external circuit with the commutator. As the shaft turns counter-clockwise, brush *g*, view (*a*), comes into contact with bar *e* and brush *h* with bar *f*.

The electromotive force generated in the turn, as soon as the conductors start to cut across the lines of force, causes a flow of electricity out through the bar *e*, the *positive brush* *g*, the external circuit, and into the armature by means of the *negative brush* *h* and bar *f*. At the end of the first quarter revolution

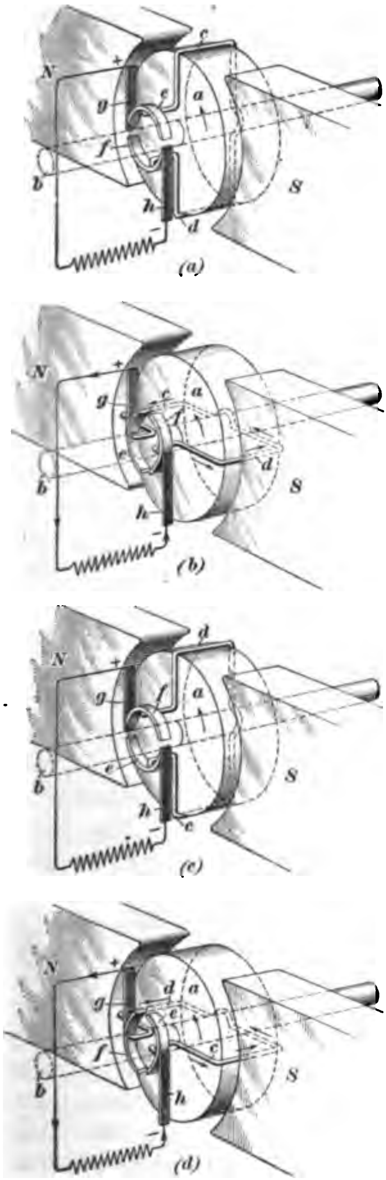


FIG. 9

the position of the armature turn, the positions of the commutator bars, and the direction of the current are as indicated in (*b*). At the end of the second quarter, the conductors *c* and *d* are generating no electromotive force and the bars are just reversing their connections to the brushes, as indicated in (*c*). At this time there is no current in the circuit. During the third and fourth quarters, the bar *f*, view (*d*), is in contact with the positive brush *g* and bar *e* is in contact with the negative brush *h*. The direction of current in conductors *c* and *d* is indicated by the arrows. At the end of the fourth quarter, the conductors are again in the positions shown in (*a*), and the commutator bars are about to reverse their connections with the brushes.

As indicated by the arrows near conductors *c* and *d*, views (*b*) and (*d*), the direction of current in each conductor is reversed because the relative direction of motion of the conductors and the direction of the flux are changed; but commutation serves to keep the current uniform in direction in the external circuit.

19. Pulsating-Current Curve.—The alternating electromotive force of the armature, indicated by the curve *a b*, Fig. 8, produces through the action of the commutator an external direct current of the form indicated in Fig. 10. The current starting at zero rises to a maximum value, decreases to zero, and repeats this action as long as the circuit is active, the current being in the positive direction at all times.

A current changing in value in the general manner indicated in Fig. 10 is called a *pulsating current*. The term, as ordinarily employed, refers to a direct current that varies in magnitude through a regular series of changes between maximum and minimum values; the minimum value may or may not be zero.

20. Armature With Several Coils.—The variations of the current, as indicated in Fig. 10, are due to the armature having only a single turn of wire. In an actual armature, there are many coils and commutator bars. The conductors of a few coils are passing through positions in which little or no electromotive force is generated in them, and their connections to the brushes are then reversed; but there are always a number of coils connected in series in the two or more parallel paths between the positive and negative sets of brushes. Therefore, the direct electromotive force impressed on the external circuit does not fall to zero, as indicated in Fig. 10, but assumes a nearly constant value for all positions of the armature conductors during a revolution.

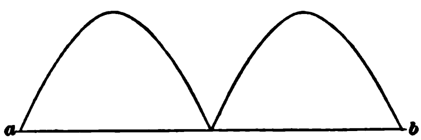


Fig. 10

21. Fig. 11 shows in a conventional manner the arrangement of several coils on an armature intended for a two-pole generator. The armature conductors are indicated by small circles *a*, *b*, *c*, etc., the commutator bars by the outlines numbered *1*, *2*, *3*, etc., and the brushes by $-B$ and $+B$. Blackened circles indicate direction of electromotive forces away from the observer; circles with dots in the center, direction toward

the observer; and white circles, conductors temporarily in positions in which practically no electromotive force is generated. Straight dotted lines joining conductors indicate connections on the rear end of the armature, and curved lines, connections with the commutator bars. An external circuit is indicated at *R*.

Two current paths can be traced from brush $-B$ to brush $+B$ as follows: $-B$-3-g-g'-2-e-e'-1-c-c'-8-$+B$, and $-B$-4-d-d'-5-f-f'-6-h-h'-7-$+B$. Coils 8-a-a'-7 and 3-b-b'-4 are short-circuited by the brushes. These coils are moving through

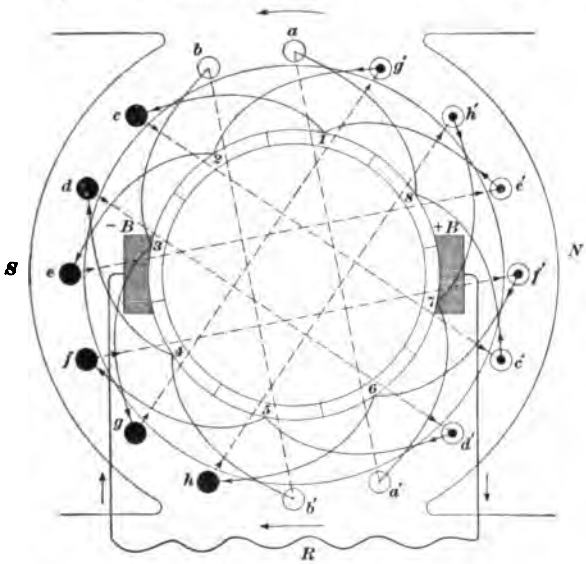


FIG. 11

spaces, called *neutral spaces*, where little or no electromotive force is generated in them; therefore, there is little current in the coils. By means of commutation, these coils are transferred from connection with one group of coils to connection with the other group; thus, the electromotive forces that will be generated in them after a little further rotative movement will act in unison with the electromotive forces generated in the group of coils to which they are connected as soon as their commutator bars leave direct contact with the brushes.

PARTS OF THE MAGNETIC FIELD

22. Main Field Magnets.—The purpose of the electromagnets that form the field magnets of an electric generator is to establish a magnetic flux. Some types of small direct-current generators have only two pole pieces, and these are known as **bipolar generators.** Large direct-current generators usually have four or more pole pieces, and these are known as **multipolar generators.**

23. In Fig. 12 are indicated by dotted lines the magnetic circuits of a four-pole, field-magnet frame and armature core.

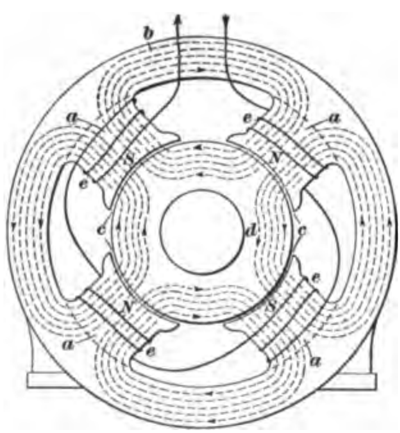


FIG. 12

The *field-magnet cores*, or pole pieces, are shown at *a*, and the *field frame*, or *yoke*, at *b*. The broadened ends of the pole pieces are called *pole shoes*, and the surfaces of the shoes near the *air gaps c* between the pole pieces and the *armature core d* are called *pole faces*. The *field coils*, or *magnetizing coils*, are shown at *e*.

The field coils, field-magnet cores, pole shoes, and the yoke, taken collectively, are called the *field of the machine*. The field-magnet cores, pole shoes, air gaps, armature core, and field yoke, taken collectively, form the *magnetic circuits of the machine*.

When the current in the exciting coils is in the direction indicated by the arrowheads, the polarity of the pole faces is as indicated by the letters *N* and *S* and the paths of the magnetic fluxes are as indicated by the dotted lines. The field frame, field-magnet cores, pole shoes, and the armature core are made of very soft iron or of steel. The reluctance of this part of the magnetic circuit is low, and the air gaps are made short to keep the reluctance of the complete magnetic circuit at a low value.

24. The magnetic circuits are so arranged that the flux enters and leaves the armature core at the proper points to establish in each air gap a magnetic field of the required distribution and density of lines. The detailed arrangements of the parts of the magnetic circuit may be varied to conform to the general design of the generator. Fig. 12 shows one arrangement of parts for a multipolar generator, and Fig. 13 an arrangement for a bipolar generator. The reference letters in Figs. 12 and 13 have the same significance.

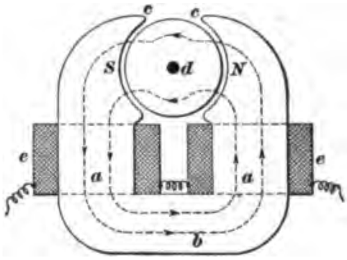


FIG. 13

25. Commutating Poles. In many direct-current generators and motors, the field frame is provided with auxiliary pole pieces located midway between the main pole pieces, and called *commutating poles*, or, rarely, *interpoles*. Their purpose is to neutralize a portion of the disturbing magnetizing effect of the flux due to the armature magnetomotive force, thus improving the commutation of the machine.

CLASSIFICATION BY METHODS OF FIELD EXCITATION

26. Magneto.—There are several methods of connecting the exciting coils of the field magnets to the armature. In some very small generators, called *magnetos*, the exciting magnetic flux is provided by one or more permanent magnets, and in such a case no winding is placed on the field magnets. Magnetos are commonly used for signaling purposes, for blasting, and for the ignition of gas engines.

The armature usually has one coil, and when equipped with a simple two-bar commutator will provide direct current for the external circuit. When two slip rings are used instead of a commutator, an alternating current is established in the external circuit.

27. Separately Excited Generator.—The flux for most commercial generators is produced by electromagnets.

Generators may be classified according to the method employed to ***energize***, or ***excite***, the field coils. In a separately excited generator, the current for energizing the field coils is provided from a source external to the generator. The connections of both the armature and the field coils are shown in Fig. 14. The exciting coils *a* are placed on the field-magnet cores and

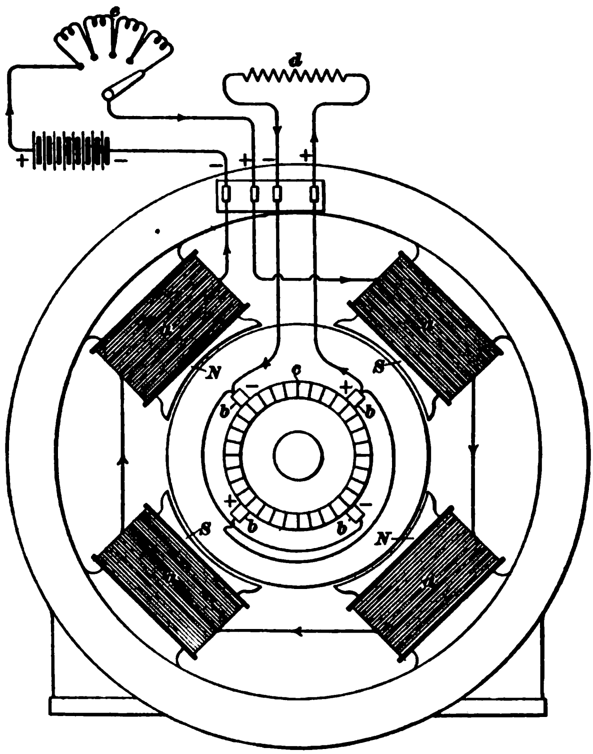


FIG. 14

connected to a battery or to another direct-current generator. Positive brushes $+b$ and negative brushes $-b$ bear on the commutator *c* and serve to impress the electromotive force generated in the moving armature conductors on the external circuit *d*. There is no electrical connection between the exciting circuit for the field magnets and the armature circuit.

The value of the electromotive force generated may be varied by changing the speed of the armature or by changing the value of the magnetic flux. The latter change may be effected by means of a variable resistance *e* in the field circuit or by changing the electromotive force causing the exciting current.

28. Shunt Generator.—Another type of machine is called a **self-exciting shunt generator**, or simply a *shunt*

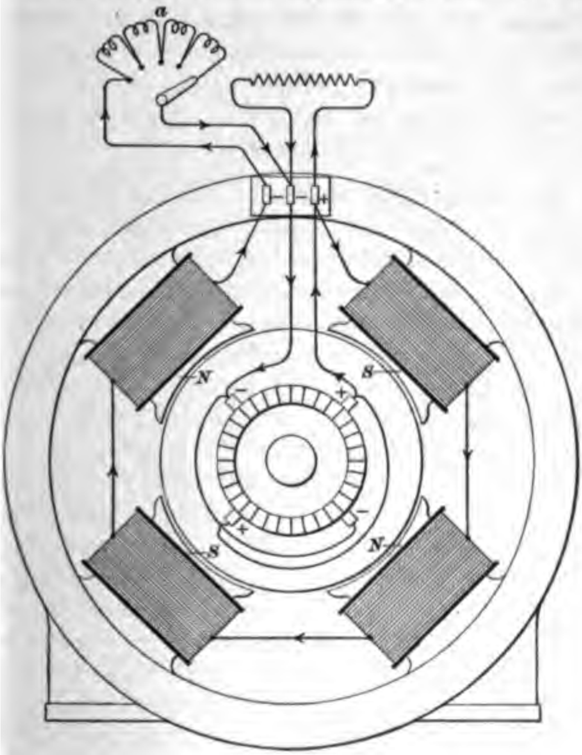


Fig. 15

generator, from the fact that the exciting current for the field coils is provided by the generator itself. The exciting circuit is connected to the brushes on the armature and is in *shunt*, or parallel, with the external circuit of the generator. A shunt,

in its broad sense, refers to a side path; when applied to an electric circuit, it refers to a side path between two points already connected.

The connections of a shunt generator are indicated in Fig. 15. The resistance device *a*, called a *field rheostat*, is included in the exciting circuit and serves to adjust the exciting current and thus regulate the electromotive force generated by the armature conductors.

The field coils of a shunt generator are formed of many turns of fine copper wire and the individual coils are connected in series, but this group of coils is connected in shunt with the armature. The resistance of the exciting circuit is high and only a very small part of the current from the armature is required to energize the field magnets.

29. Building Up a Magnetic Flux.—In order that a self-exciting machine may start to generate, some residual magnetism is required in the field of the generator. The frame of even a new machine is often slightly magnetized, but if it is not magnetized sufficiently, or if it is of incorrect polarity, the field coils may be separately excited temporarily from another generator or from a few cells of battery. The shunt circuit is then disconnected from the separate source and connected to the brushes of its own armature.

The slight electromotive force generated by the armature will establish a current in the exciting circuit. This will increase the inducing flux, resulting in an increase of electromotive force and further building up of the exciting current and the flux. As the exciting current increases, the cores of the field coils approach saturation; therefore, a given increase in current results in less increase of flux. A point of balance of the electrical and magnetic effects is finally obtained where the generated electromotive force and the exciting current become constant for existing conditions of operation. The operation of setting up the magnetic flux is termed *picking up*, or *building up*, the flux.

30. Series Generator.—Another type of self-exciting machine is the series generator. The exciting coils are connected

in series with the armature and the external circuit, as indicated in Fig. 16. No electromotive force, except the slight value due to residual magnetism, is generated in the armature unless the external circuit is closed and a current is established throughout the circuit. The electromotive force generated depends on the value of the current in the circuit, which consists of the

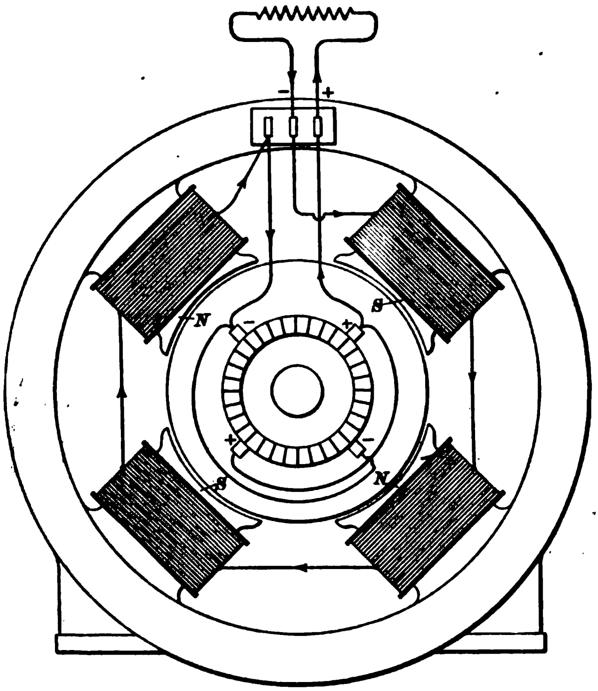


FIG. 16

field coils, the armature, and the external circuit. The field coils are formed of a conductor of comparatively large sectional area, and each coil has comparatively few turns.

31. Compound Generator.—Automatic regulation of the electromotive force of a generator may be effected by a combination of shunt- and series-field coils forming part of a compound-wound generator, connections for which are shown in Fig. 17. The shunt coils are shown at *a*; the main series

coils, at b; and the coils for the commutating poles, at c. The coils for the commutating poles are connected in series with the armature and with the series coils on the main pole pieces. These commutating poles are not always used with compound generators.

In a generator as usually connected, the magnetomotive forces of the shunt coils a and the series coils b act in unison

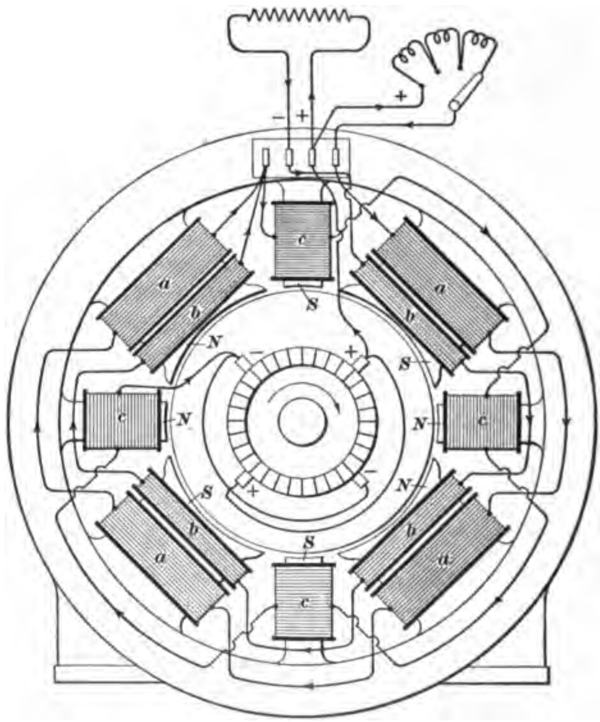


Fig. 17

to set up fluxes in the cores of the main field magnets. The magnetomotive forces of the coils c establish fluxes that partly neutralize the effects of the fluxes set up by the armature conductors.

When the generator is running, but is not connected to the external circuit, the magnetomotive forces of the shunt coils a produce the flux of the magnetic field of the machine. With

the connections of the shunt coils shown, the shunt current passes through the commutating coils *c*, but as both the shunt current and the number of turns of coils *c* are small, the magnetomotive force of coils *c* are of low value.

When the external circuit is closed, current is established in the main series coils *b* and the commutating-pole coils *c*. The fluxes in the cores of the main field magnets are increased and a higher electromotive force is generated. If the load on the generator increases still further, the exciting current through the series coils increases, thus building up the fluxes in the magnet cores and causing a higher electromotive force to be generated. This higher electromotive force is desired because of the increased drop in volts necessary to force the larger load current through the armature, the external circuit, the series-field coils, and the commutating coils.

32. The preceding method of regulating the electromotive force of the generator is called **compounding.** A machine is *flat-compounded* when the magnetomotive force of the series coils is adjusted so that the voltage at the generator terminals remains practically constant for all loads. It is said to be *overcompounded* when the voltage at the terminals rises as the load increases so that some distant point on the external circuit may have nearly constant voltage for all loads.

In an *accumulatively compounded* generator, the shunt coils and series coils are so connected to their respective circuits that they act in unison to establish the inducing flux and thus to increase the generated electromotive force as the load increases.

In a *differentially compounded generator*, the connections of the shunt and series coils are such that the magnetomotive force of the series coils acts in opposition to, or *bucks*, that of the shunt coils. Generators of this kind are used in automobiles and to a limited extent for other purposes. If the speed of a variable-speed generator exceeds a given value, the electromotive force at the terminals does not increase because of the bucking effect of the series coils.

The words *accumulatively* and *differentially* are most commonly used in connection with the field windings of direct-current motors. Compound-wound machines, both generators and motors, are usually connected accumulatively, and this connection is always understood when the other is not stated.

THE ELECTRIC MOTOR

COMPARISON OF GENERATORS AND MOTORS

33. A **motor** may be defined as a machine for converting electrical energy into mechanical energy. The force necessary to maintain rotation of the motor armature and thus cause the motor to perform work is supplied by the interaction of the flux of the field magnets and that of the armature conductors.

Any direct-current generator can be operated as a motor by impressing on its terminals an electromotive force. As in the case of generators, motors may be classified according to the method of energizing their field magnets as *shunt*, *series*, and *compound motors*.

THEORY OF MOTOR ACTION

DEVELOPMENT AND DIRECTION OF TURNING FORCE

34. Motor Action of Conductor Flux.—Fig. 18 shows one arrangement of conductors on an armature intended for a four-pole motor. The conductors, lying in slots in the armature core, and the direction of current in each conductor are represented in a manner similar to that in Fig. 11. Arrows near the pole faces, Fig. 18, indicate the direction of the field flux, and a loop with arrowheads drawn around one pair of armature conductors opposite each pole face indicates the paths of the flux set up by current in these conductors. To avoid confusion of lines, only a few paths for conductor flux are shown. The denser flux on the side of each conductor where the directions

of the two fluxes agree tends to move all conductors so as to cause counter-clockwise rotation of the armature, as indicated by the curved arrow near the brushes A and B.

35. As the armature rotates, successive commutator bars slide under the brushes so as to reverse the direction of current in each conductor while the conductor is passing through the

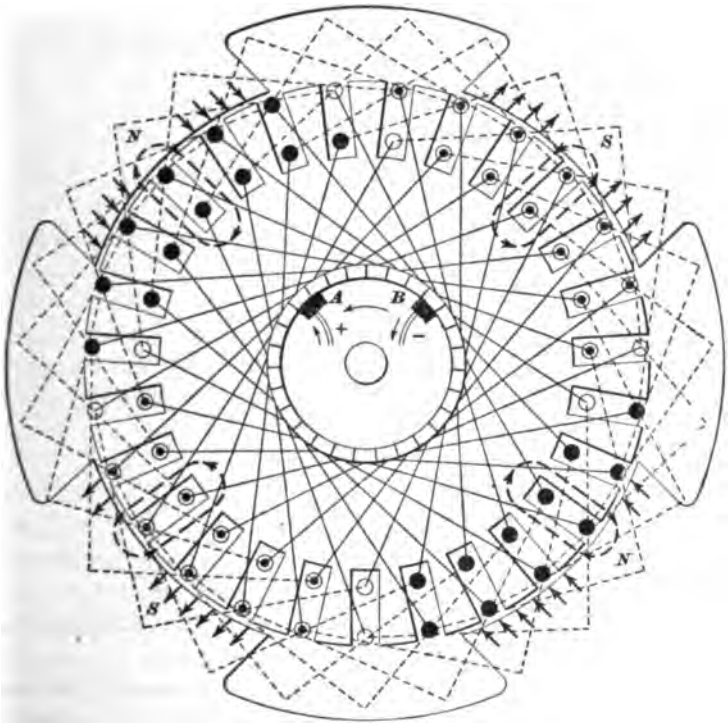


FIG. 18

neutral space. The result of commutation, therefore, is that all conductors adjacent to north poles carry current in one direction and all the conductors adjacent to south poles carry current in the opposite direction, as indicated in Fig. 18. The reaction between the flux of the poles and the conductor flux thus maintains the turning effort, or **torque**, tending to rotate the armature. While the torque due to each armature

conductor may be small, the total torque due to all the conductors may be very large.

36. Motor Action of Armature Poles.—The rotation of an armature may also be explained by considering the magnetic action of the poles of the field magnets on the poles formed on the armature core by the magnetomotive force of the armature windings.

In Fig. 19 is shown a four-pole motor. When current enters the armature windings at brush *A* and leaves at brush *B*, the directions of the currents in groups of conductors *C*, *D*, *E*, and *F* are as indicated. The fluxes around the individual conductors combine to form poles on the armature core midway between the tips of two adjacent pole pieces, as indicated at *N′* and *S′*. Unlike poles of the field magnets and of the armature core attract each other; therefore, in Fig. 19, a clockwise rotation of the armature is established.

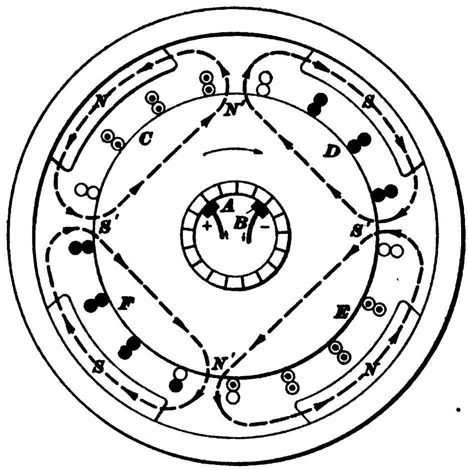


Fig. 19

The connections of conductors and commutator bars in Fig. 19 differ from those in Fig. 18. The direction of current in the conductors near corresponding poles in Fig. 19 is opposite to that in Fig. 18, thus accounting for the opposite direction of rotation.

The individual armature conductors change from one group to the adjacent group as the armature rotates, but as the direction of current in the individual conductors changes during this action, owing to commutation, the direction of the current in a group of conductors, the polarity and location of the poles

formed on the armature core, and the direction of rotation of the armature remain unchanged.

The armature poles are not sharply defined, but the lines of force stray somewhat, entering or leaving the core for a considerable space each side of the points indicated by the letters N' and S'.

37. **Reversal of Rotation.**—The direction of rotation of the armature of a direct-current motor may be reversed either by exchanging the terminals of the exciting circuit of the field magnets, thus reversing the polarity of the pole pieces, or by exchanging the connections of the armature leads to the brushes, thus reversing the polarity of the brushes and changing the direction of the current in corresponding groups of armature conductors. For example, if the brush A, Fig. 19, were made the negative one, the current in group C conductors would be downwards and that in group D conductors, upwards, etc. This results in a reversal of polarity of the poles on the armature core and of the direction of rotation of the armature. If a south pole S' were formed at the top of the armature core, Fig. 19, it would be attracted toward the north pole on the frame, and the rotation would be counter-clockwise. If the terminals of both the field circuit and the armature windings are reversed, the direction of rotation will remain unchanged.

38. The reversal of rotation may be explained by considering the action of a single conductor. In Fig. 1, the direction of movement due to motor action is in each case indicated by the horizontal dotted line arrow near the conductor $a\,b$. This arrow in all cases is opposite in direction to the arrow indicating direction of movement of the conductor when acting as a generator. It should be noted that in (a) and (d), where the flux of the magnet is reversed in direction and the direction of the current in the conductor remains unchanged, the direction of motor action is reversed, as indicated by the dotted horizontal arrows. The direction of motor action is also reversed in (a) and (b), where the direction of the flux from the magnet is unchanged, but the direction of current in the conductor is reversed. In (a) and (c), both the flux of the magnet and the

current in the conductor are reversed in direction and the direction of motor action remains unchanged.

39. If a machine that has been operating as a shunt-wound generator is operated as a shunt-wound motor, the polarity of the circuit wires and the connections between the circuit and the machine being unchanged, the armature will rotate as a motor in the same direction as it did as a generator.

Current now passes into the armature at the positive motor brushes, which are the same as the generator positive brushes. This causes a reversal of the direction of the current in the armature windings. The polarity of the pole pieces remains unchanged, because the same end of the field-coil circuit is connected to a circuit wire of the same polarity as before.

In Fig. 1 (*a*), the generator conductor *a b* is moved by some external force toward the right as indicated by the horizontal full-line arrow. In (*b*), the direction of the current in the motor conductor *a b* is reversed, but the flux of the magnet is unchanged in direction, and the direction of the motor action is toward the right, as indicated by the horizontal dotted-line arrow. The movement of the generator conductor and of the motor conductor under these conditions is in the same direction.

COUNTER ELECTROMOTIVE FORCE

40. When an armature conductor is forced by motor action to move across the flux of the field magnets, an electromotive force is generated in it. This electromotive force is usually called **counter electromotive force** (generally written counter E. M. F.), but it is also known as *motor electromotive force*, *back electromotive force*, and *back voltage*.

An armature has but a very low resistance—a fraction of an ohm in many cases—and if the armature is clamped so that it cannot rotate and the full voltage of the line is then impressed on its terminals, the windings would probably be damaged by the resulting large current.

If the armature is free to rotate, the counter electromotive force established in the active conductors acts in direct opposition

to the impressed electromotive force from the power circuit and thus limits the current. As the speed increases, the counter electromotive force increases and the armature finally reaches such a speed that the opposing action of the counter electromotive force plus that due to the ohmic resistance of the windings is such that just enough current is taken by the motor to develop the required torque. In the case of a shunt motor, if the load changes, the speed varies slightly and there is automatically established a new value of the counter electromotive force that is suitable for the new value of the current required for the motor load.

The pressure that is actually effective in forcing current through the armature is the difference between the impressed electromotive force and the counter electromotive force. This difference is usually only a few volts, because the ohmic resistance of the armature is so low that only a low effective voltage is required to force the current through the windings.

EXAMPLE.—The armature of a motor has a resistance of .25 ohm between brushes and is designed to operate with an impressed voltage of 500. What would be the current: (*a*) if the armature were held stationary and the full voltage applied? (*b*) if the armature were free to rotate and a counter electromotive force of 490 volts were generated in the windings?

SOLUTION.—(*a*) If the armature is standing still, no counter electromotive force is generated; hence, the current is equal to

$$\frac{\text{impressed electromotive force}}{\text{resistance}} = \frac{500}{.25} = 2{,}000 \text{ amp.} \quad \text{Ans.}$$

(*b*) If the armature were free and generating a counter electromotive force of 490 volts, the voltage that is effective in forcing current through the armature windings is $500 - 490 = 10$, and the current is

$$\frac{\text{effective electromotive force}}{\text{resistance}} = \frac{10}{.25} = 40 \text{ amp.} \quad \text{Ans.}$$

PURPOSE OF STARTING RESISTANCE

41. In very small motors, the voltage of the line is impressed directly on the armature terminals, because these armatures have a comparatively high ohmic resistance. In larger motors, the impressed voltage is adjusted to a lower value for starting

the motor by the insertion of an adjustable resistance, called a *starting rheostat*, in the armature circuit. As the speed and counter electromotive force of the armature increase, the resistance of the rheostat is gradually cut out of circuit until, finally, the armature is connected directly across the line wires. Rheostats and other auxiliary devices intended for the control of motors are described in a later Section.

COMMUTATING-POLE MOTORS

42. The poles on the armature core formed by the current through the windings, as shown in Fig. 19, cause a magnetic flux in the space midway between the poles, so that the armature conductors of a coil when moving through this space may have an electromotive force generated in them during the time that the coil is short-circuited by the brush. The generation of a very small electromotive force under these conditions may cause a considerable current in the coil and sparking at the commutator under the brushes. The action of commutating poles is to oppose and prevent the disturbing flux in the space where the conductors of a coil are short-circuited. These poles therefore establish between the poles a space in which commutation can occur with practically no sparking.

The relative location of the main poles and the commutating poles is the same in a motor as in a generator, Fig. 17, but a commutating pole of a motor has the same polarity as that of the adjacent main pole behind it, considering the direction of rotation of the armature as forward. The exciting coils for the commutating poles are in series with the armature; therefore, if the polarity of the armature poles is reversed, the polarity of the commutating poles is also reversed. This arrangement permits of good commutation with fixed brushes at all loads and in either direction of rotation of the armature.

DIRECT-CURRENT GENERATORS

CLASSIFICATION

1. An **electric generator** is a machine for converting mechanical energy into electric energy. If the flow of electric energy, or electricity, from the machine is continuously in one direction, the machine is a *direct-* or *continuous-current generator;* if the current of electricity alternates in direction, the machine is an *alternating-current generator*, or an *alternator*. Alternators and other alternating-current machinery are discussed in other Sections.

2. According to output, direct-current generators are classed as *constant-potential*, or *constant-voltage*, *machines* and *constant-current machines;* constant-voltage machines are much more generally used. Voltages of 110 to 125 are common for electric lighting and for the operation of some comparatively small motors; 220 to 250 volts are used for most industrial motors and for some systems of lighting; and 500 up to 2,400 volts are used for direct-current electric-railway systems. For 2,400 volts, however, two 1,200-volt machines are connected in series.

Constant-current generators are little used in America, except for some old systems of electric lighting in which arc lamps are connected in series. Abroad, however, constant current is used in some large systems for transmitting electric energy long distances. This system of transmission is known as the *Thury system*, from the French engineer who was most active in developing it. It has some decided advantages that will probably bring it into more general use.

3. According to input, or method of driving generators, they are classed as ***direct-driven***, ***belt-driven***, ***gear-driven***, etc. Generators direct driven by steam engines are generally called ***engine-driven***, or ***engine-type***, ***generators;*** those direct driven by steam turbines are called ***turbine-type generators***, or ***turbo-generators***. All generators for direct drive must be designed to develop their outputs at the speeds of their drivers, or prime

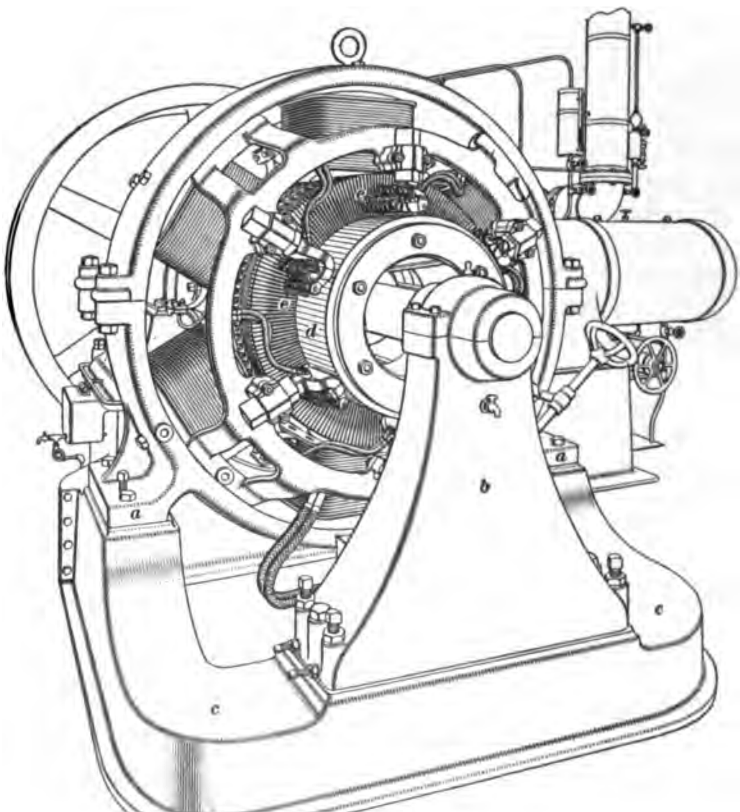


FIG. 1

movers; those for belt or gear drive may be designed for any speed within the limits made possible by practicable pulley and gear ratios.

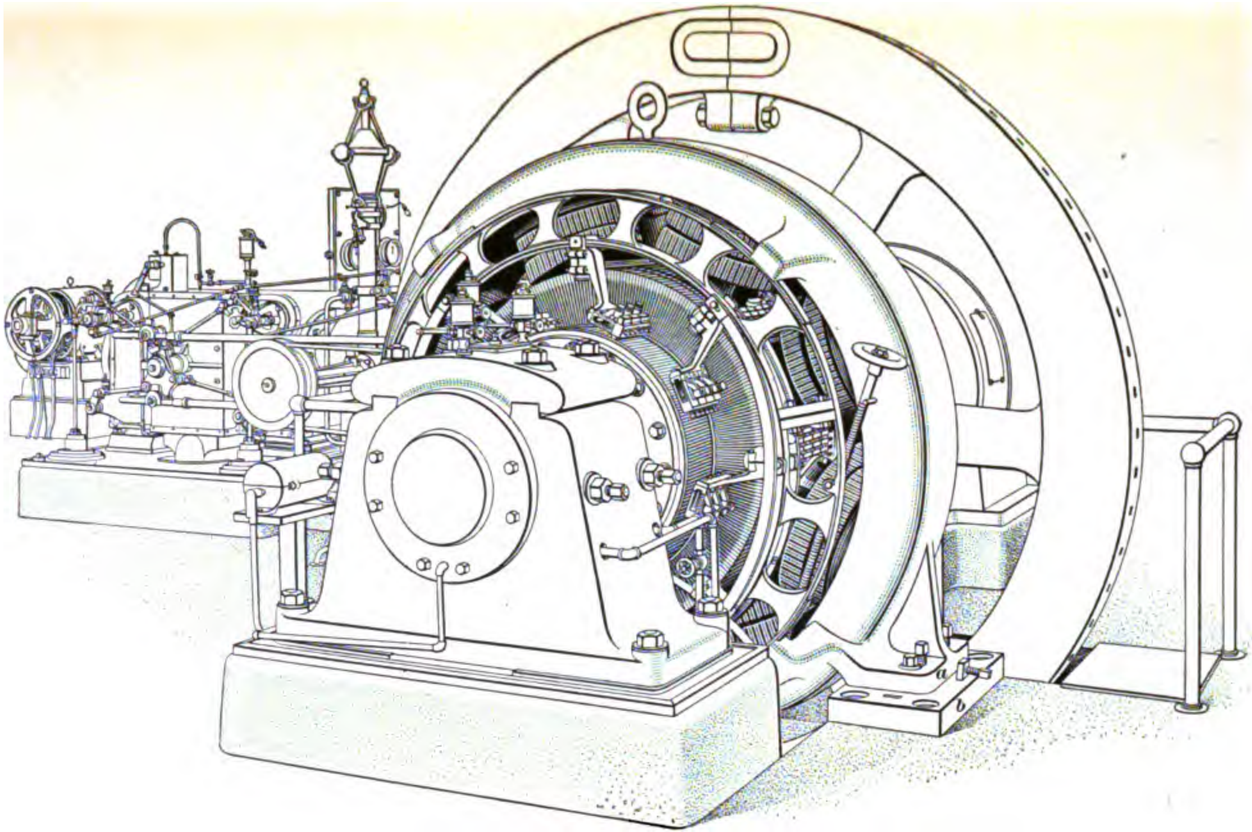


Fig. 2

4. Fig. 1 shows a typical engine-type generator. The feet *a* of the generator frame and the pedestal bearing *b* rest on an extension *c* of the engine base, or bedplate. Fig. 2 shows a larger engine-type generator supported on a separate foundation; the feet *a* rest on *sole plates* *b*, and the bearing pedestal

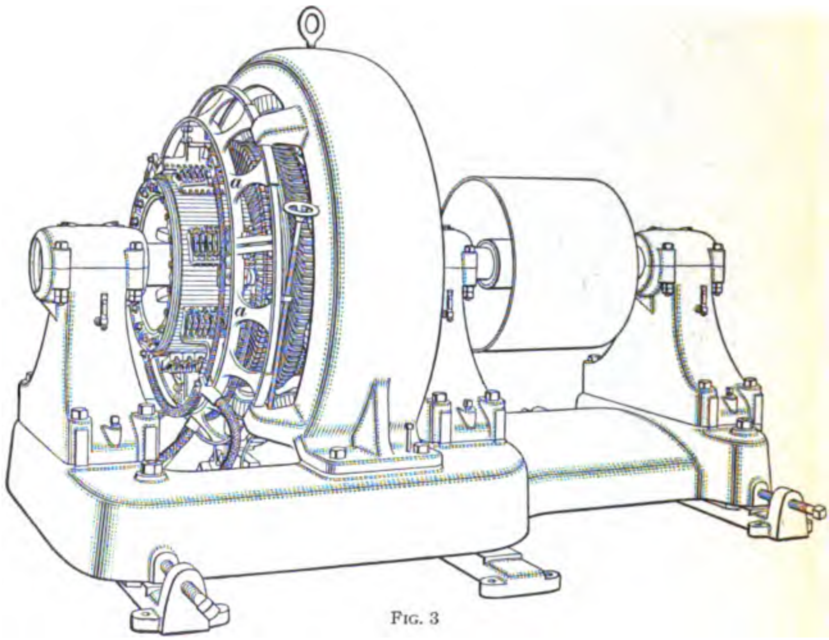


FIG. 3

stands on a concrete foundation. The shafts, bearings, and bearing pedestals of engine-type generators are usually supplied by the engine builders as parts of the engine.

Fig. 3 shows a three-bearing belt-driven machine with a base, bearing pedestal, slide rails, and tension screws for shifting the generator to adjust the belt pull. Fig. 4 shows a steam turbo-generator resting on a base that also supports the turbine, making the whole a complete, compact unit.

5. Direct-current generators are also classed as commutating-pole and non-commutating-pole machines. On generators for large outputs at high speeds, smaller poles placed

midway between the main poles and excited by current in coils connected in series with the armature greatly improve commutation; such poles are called *commutating poles*. In Fig. 4 a commutating pole is shown at *a* and a main pole at *b*. Other special features are added in some cases to aid commutation,

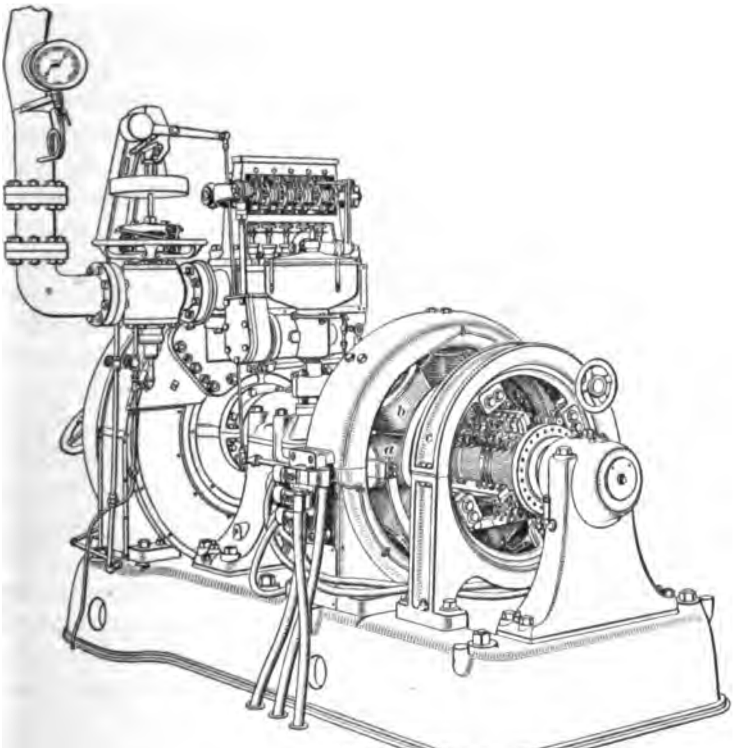


FIG. 4

as will be explained later. Commutating poles are usually omitted from small generators, especially those operating at slow speeds, because the advantages gained by their addition are not enough to warrant the additional expense involved in their construction.

CONSTRUCTION

GENERAL ARRANGEMENT

6. The essential features of a direct-current generator are a field structure and an armature with a current-collecting device. The armature consists of a laminated iron core, cylindrical in form, on or near the surface of which are conductors forming the armature windings. The current-collecting device is nearly always a commutator, but collector rings are used on one type of direct-current machine described later. The field structure usually consists of a circular yoke with inwardly projecting radial poles; in general, each pole is provided with an exciting coil, or field coil.

ARMATURES

CORES

7. As an armature rotates, the direction of magnetic flux in every part of the armature core changes. Energy is required to change the direction of flux in iron; this energy serves no useful purpose and is therefore a loss, called **hysteresis loss.** The hysteresis loss is lower in some grades of iron and steel than in others, and a special grade of steel, called *electrical steel*, in which the hysteresis loss is low, is used for the cores of direct-current armatures in order to lessen the hysteresis loss in them.

8. Furthermore, the continual change in direction of magnetic flux in the body of the core causes the development of electromotive forces that would set up currents in a solid iron core somewhat as shown in Fig. 5. This illustration represents the lower half of a solid core, and the closed loops with arrowheads represent the direction of local currents in such a core.

These so-called *eddy currents* constitute a loss because they serve no useful purpose. The strength of eddy currents, or the **eddy-current loss**, depends on the resistance of their paths. In order to make this resistance high, and the eddy-current loss low, armature cores are practically always made of thin disks, or laminations, punched from electrical-steel plates. The thinner these laminations are, the lower is the eddy-current loss. For high-speed machines in which the flux changes are rapid, the laminations are usually punched from sheets .014 inch thick. For slower speeds, thicker laminations are permissible, .02-, .03-, and even .04-inch laminations being used in some cases. The punchings are separated from one another by some insulating material, such as paper, japan, paint, varnish, or enamel, in order to prevent the formation of eddy currents between adjacent punchings.

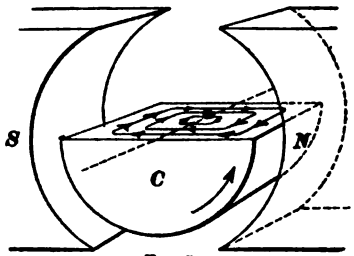


FIG. 5

9. Hysteresis loss and eddy-current loss are difficult to determine separately and are often referred to collectively as **core losses** and sometimes as *iron losses*. The effect of these losses is to heat the core, so that an armature rotating in a magnetic field becomes warm even when no electricity is flowing in the armature conductors.

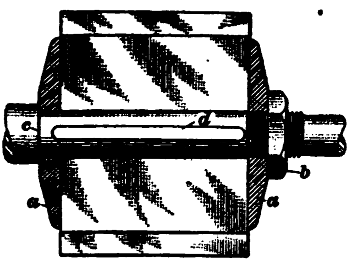
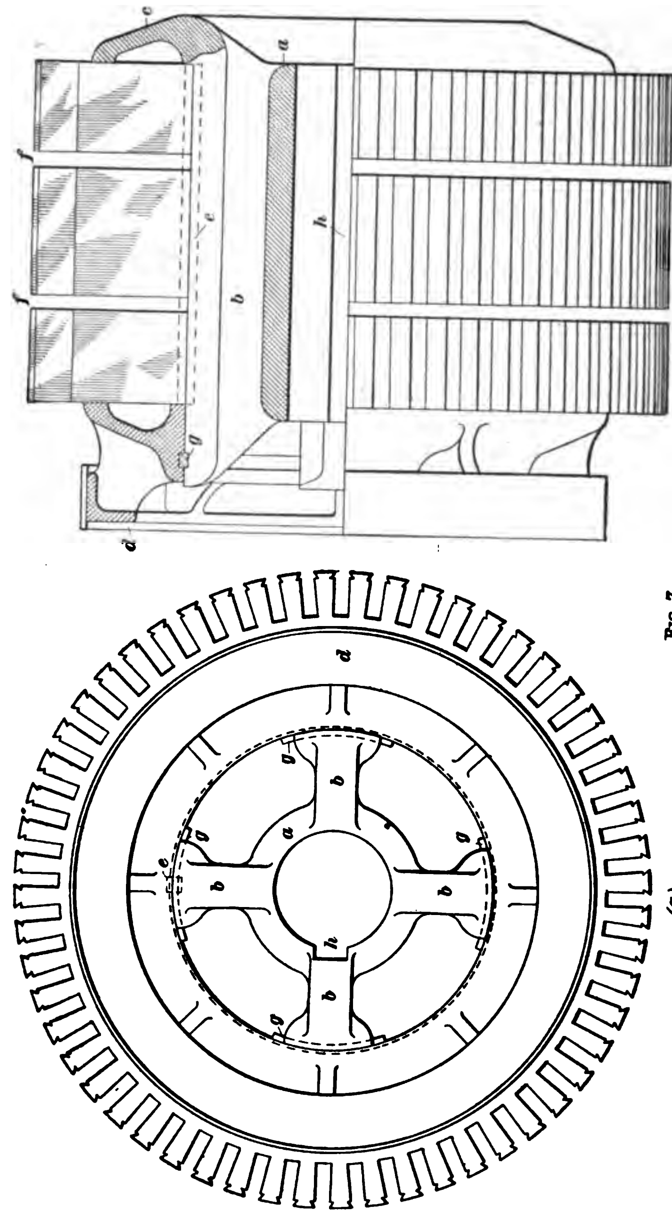


FIG. 6

10. The punchings of the armature core are usually held in line by a shaft or an armature spider passing through a central hole, and they are clamped together between end plates. In Fig. 6 is shown a section of an armature core for a bipolar generator. The punchings are held firmly in place between the end plates *a*, usually of cast iron, which are clamped between a nut *b* and a shoulder *c*, on the shaft. A



(a) (b)

FIG. 7

key in the keyway *d* projects into a suitably cut notch in each punching, to prevent the core from turning on the shaft.

11. The construction of another form of armature is shown in Fig. 7, in which view (*a*) represents a cross-section, or a section in a plane perpendicular to the shaft, and view (*b*) a longitudinal, or side, view, the upper part being in section. Each part visible in both views is referred to by the same letter in both. The punchings are mounted on a cast-iron spider consisting of a hub *a*, four arms *b*, and an end flange *c*, all cast in one piece. The rear end flange *d* is a separate casting, and its central hole is bored out to the same diameter as the central hole in the punchings, so that it may slip over the arms of the spider. The punchings are notched to fit the key *e*, which is inserted in the arm *b*. At intervals in the core are spacers, or vent plates, consisting of strips on edge attached to an armature punching. They provide the core with radial air passages, *f* called *vents*, *ducts*, or *flues*, through which air circulates when the machine is running and helps to keep it cool. The rear plate, or flange, *d*, is pressed on and small keys *g* are inserted in the grooves in the spider arms to secure the parts together. A keyway *h* is provided in the hub of the spider for securing it to the shaft. A ring for supporting the rear end windings is cast with the flange *d*, and the arms that support this ring are arranged to fan air through the windings.

12. In Fig. 8 are two sectional views showing the construction of an armature and a commutator for a large engine-type generator. The armature is of too great a diameter for the punchings to be made in a single disk each, so they are made in segments. Each segment has two dovetail lips *a* that fit into accurately machined recesses in the arms of the spider. The punchings are so assembled that the joints *b* in one disk are midway between the joints *c* of the next disk. The punchings are clamped between the end plates *d* and *e* by the bolts *f*. These end plates are centered by providing them with flanges *g* machined to fit the spider.

It is customary to arrange the armature of an engine-driven generator so that it can be shipped complete, either with or

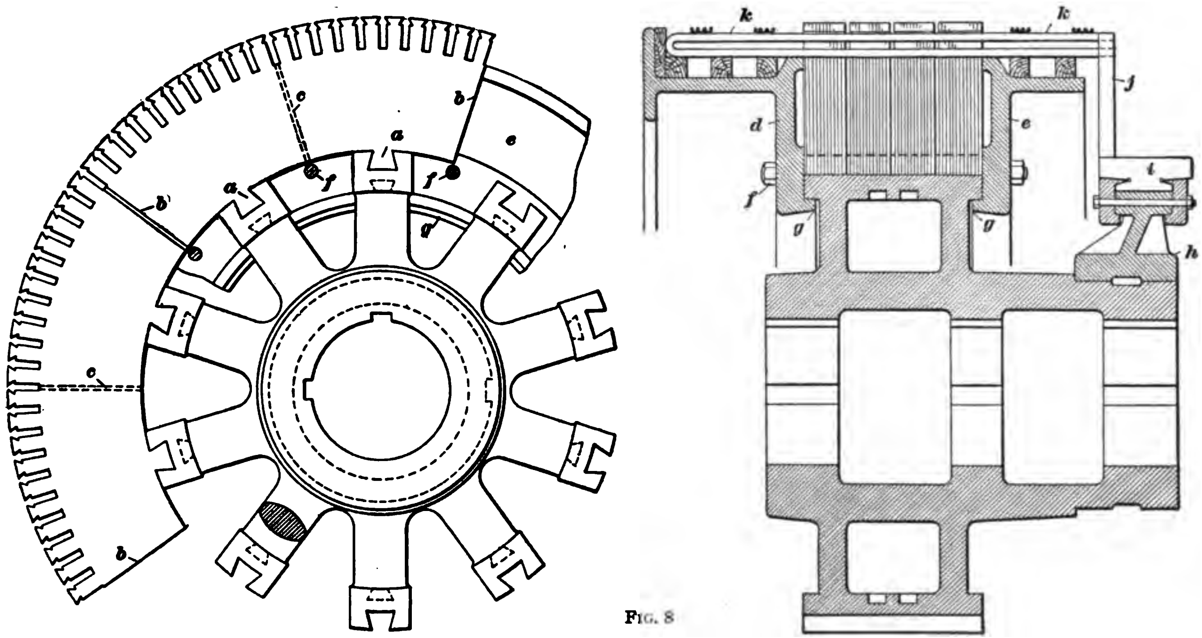


FIG. 8

without the engine shaft. The hub of the armature spider must therefore be extended, as shown in Fig. 8, so as to support the commutator spider *h*. The commutator segments *i* are clamped in place, and the connections *j* lead to the windings *k*.

COMMUTATORS AND BRUSHES

13. The general appearance of finished commutators can be seen in the preceding illustrations, as at *d*, Fig. 1, and the brushes can be seen at *e*. A commutator usually consists of hard-drawn or drop-forged copper segments alternating with mica or micanite segments, all clamped together by ***wedge rings***, either at the ends or underneath the segments, or by ***shrink rings*** over the top of the segments. The wedge rings and shrink rings are insulated from the copper segments by

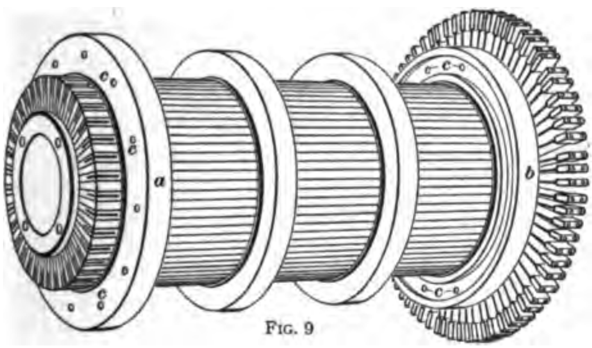


FIG. 9

micanite cones and bands. *Micanite* consists of very thin pieces of mica pasted together with shellac or other varnish. The commutator shown in section in Fig. 8 illustrates the method of clamping the segments *i* from the under side. The wedge rings may be made either in a single piece or in segments. Wedge-ring commutators are used for generators of slow and moderate speeds, while shrink-ring commutators are used for high-speed machines.

14. A commutator of the shrink-ring type is shown in Fig. 9. The outer and inner rings *a* and *b* are drilled and tapped at *c* for the insertion of small balance weights. This

commutator is intended to be pressed directly on to the shaft, and not to be mounted on the armature spider.

15. The commutator diameter is customarily made from two-thirds to three-fourths the diameter of the armature, and the length must be great enough to give the required current capacity. Low-voltage generators therefore have longer commutators than high-voltage generators of the same power output. The current is usually collected by carbon brushes rubbing on the surface of the commutator, and for the best results the current density in the rubbing surface should not generally be over 40 or 45 amperes per square inch. As the brushes must be of such thickness as to touch not more than two or three commutator bars simultaneously, several brushes must sometimes be arranged side by side to obtain the necessary carrying capacity.

On very low-voltage, large-current generators, brushes of metal or of metal-and-graphite compound are used, and in them the current density may be from 100 to 200 amperes per square inch of conducting surface. This high current density permits the use of commutators that are much shorter than would be required with carbon brushes.

16. High-speed generators, as shown in Fig. 4, must have commutators with comparatively small diameters in order to prevent high centrifugal stresses. The required commutator surface must then be obtained by increasing the length. The commutator shown in Fig. 4 is so long that the brushes are carried by a special yoke *c* over the center of the commutator instead of being supported from the magnet frame in the usual way.

17. The **brushes** of all direct-current generators are stationary and are held against the commutator by springs. The brushes are usually attached to a ring or its equivalent that can be rotated or rocked around the commutator so as to shift them into the position for best commutation. The rocker ring is shown at *a*, Fig. 3, and is inside the special yoke *c*, Fig. 4. In each illustration is shown a hand wheel for shifting the position of the brushes by means of a screw.

ARMATURE WINDINGS

18. The voltage generated in a single armature conductor is usually so small that many such conductors must be connected in series on a generator armature in order to obtain the required voltage. Armature windings are connected with this point in view. They are of two general types, *ring windings* and *drum windings*.

19. Ring Windings.—Ring windings are comparatively little used, but their general features should be understood. Fig. 10 shows the principle. A laminated iron ring forms the armature, the supporting structure of which is not here shown. The winding is a continuous spiral, which is connected at regular intervals with the segments of a commutator. The illustration shows every turn so connected, but several turns may sometimes intervene between segments.

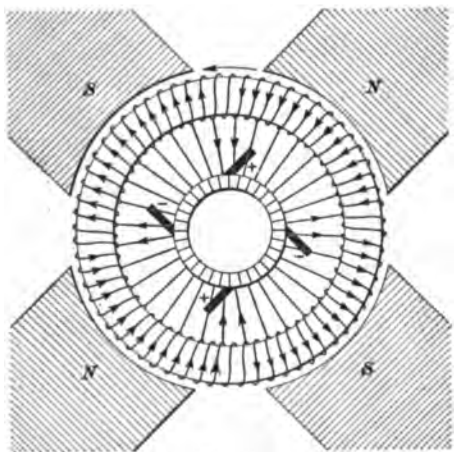


FIG. 10

Only the conductors on the side of the ring nearest the pole faces cut lines of force, except a few stray lines, for practically all the flux follows the ring between adjacent poles instead of crossing the open space in its center. With the direction of rotation counter-clockwise, as indicated by the curved arrow above the ring, Fig. 10, the direction of electromotive force in the armature conductors must be as shown by the arrowheads on those conductors; that is, the flow of electricity is from the negative brushes to the positive brushes through the armature and from the positive brushes to the negative brushes through the external circuit, which is not represented.

20. Drum Windings.—Drum windings consist of coils, both sides of which cross the face of the armature core where they pass close to the pole faces and thus cut lines of force. In rare cases, the coils are laid on the surface of a smooth core and are held in place by projecting pins and by bands around the core over the completed windings. But usually the sides of the coils lie in slots in the surface of the core, as shown in Figs. 11 and 12; wedges in grooves near the tops of the slots or bands of wire over the core hold the coils in place.

21. Drum windings are of two kinds, *series*, or *wave*, and *parallel*, or *lap*. Fig. 11 shows a bundle of four series coils of a single turn each arranged for assembling in the slots. For simplicity, the armature core is shown as being flat instead of

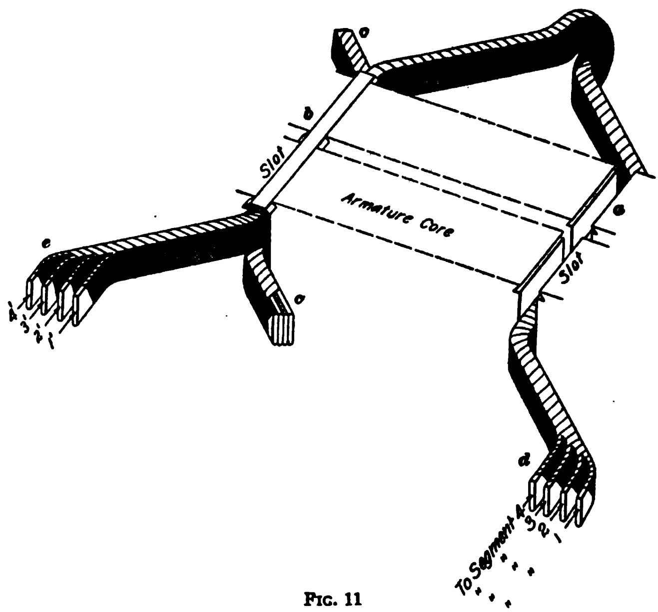


FIG. 11

in its true cylindrical form, and only the slots occupied by the coil are indicated. Each coil is separately taped to insulate it from the others, and then the bundle is taped to insulate the coils from the core and from the supports for the end windings.

The bundle of coils in Fig. 11 is so placed on the armature core that one side lies in the bottom of slot *a* and the other side in the top of slot *b*. In the bottom of slot *b* is shown a part of a coil *c* exactly the same as the bundle of coils *a b*. In the completed armature, each slot will have a bundle of conductors in the top and a bundle in the bottom, and is therefore said to have four coils per slot. The slot *b* is shown completely filled with its conductors, and a retaining wedge is shown over the coils. The coils are so made as to span the slots from *a* to *b*, this distance being approximately that of the ***angular pole pitch***, or the distance between the center lines of adjacent field poles. The coils at the end *d* are spread out to fit into four commutator segments. At the end *e*, the coils are again spread out, to go into other commutator segments, and *1'*, *2'*, *3'*, and *4'* are, respectively, the other ends of the coils marked *1*, *2*, *3*, and *4* at *d*.

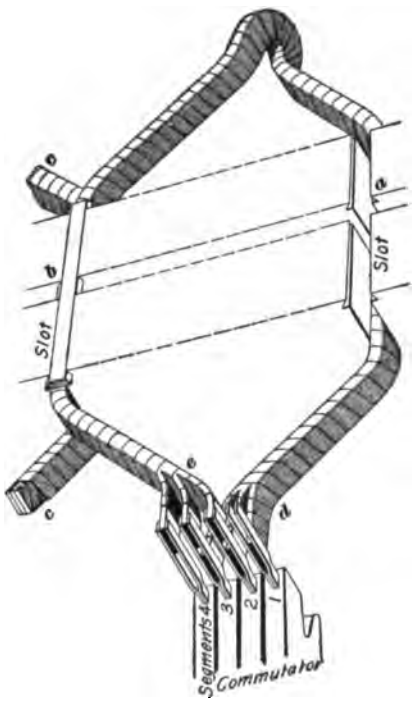


FIG. 12

22. In Fig. 12 is shown a bundle of three parallel coils connected to commutator segments *1*, *2*, *3*, and *4*. The sides of the coils lie in slots *a* and *b*, spaced about a pole pitch apart; a side *c* of another bundle of coils is shown in the bottom of slot *b*, making a winding with three coils per slot. All slots are similarly fitted in the completed armature. The coils at the ends *d* spread out and are connected to the lower part of the commutator necks of segments *1*, *2*, and *3*, while the ends *e* connect to

the upper part of the necks of segments *2*, *3*, and *4*, so that coil *1* begins at segment *1* and ends at segment *2*. Coil *2* begins at segment *2* and ends at segment *3*, etc. It is true of all parallel-type windings that if one end of a coil connects to a certain segment, the other end will connect to the next segment, either to the right or to the left of it.

23. In a series winding, the ends of each coil, as at *d* and *e*, Fig. 11, are separated by about the pitch of two poles. A series of $\frac{P}{2}$ such coils placed end to end will therefore extend around the commutator, P representing the number of poles. If the ends *d* and *e* were separated exactly two pole pitches, the series would end at the exact starting point; but the number of segments in the commutator of a series-wound armature is so selected that a series of $\frac{P}{2}$ coils will extend around to a segment next to the starting point, one side or the other. The spread of the coil from *d* to *e* is usually stated by the number of commutator segments between the ends of the coil, as from *1* to *1'*, including the segment to which one end of the coil is attached, as *1* or *1'*. This spread may be called the *commutator connecting pitch*, and may be represented by Y. Then the number of segments in the commutator is one more or less than $\frac{P}{2}Y$; in other words, the number of segments must be $\frac{PY}{2} \pm 1$.

24. The series winding in most common use has only two paths, or circuits, between positive and negative brushes, but a parallel winding has as many paths as there are poles. For a two-pole machine, each winding has two paths, and the two windings are practically identical. If C is the number of coils on an armature and P the number of poles of the field, the number of coils in each path of a series winding is $\frac{C}{2}$ and in each path

of a parallel winding $\frac{C}{P}$. When the number of poles is greater than 2, the series winding has fewer paths but more coils in series in each path. If the same size of conductor is used in both windings and the same voltage generated in each coil, the parallel winding has $\frac{P}{2}$ times as much current capacity as the series winding, and the series winding will generate $\frac{P}{2}$ times as much voltage as the parallel winding, but both armatures have the same power capacity.

25. To obtain low voltage from a generator, a parallel winding with one turn per coil, Fig. 12, and a small number of coils is used. In designing machines for higher voltages, the number of coils and segments is usually increased until

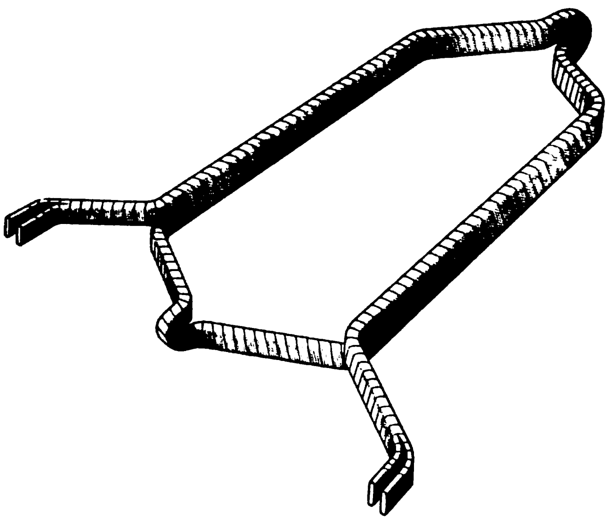


FIG. 13

the limit of the number of segments that can be made into a commutator of a given diameter is reached. Beyond this limit, a series winding with one turn per coil, Fig. 11, can be used. For still higher voltages, the number of segments and

coils can be increased, and, when the maximum number of segments for the commutator is again reached, then a series winding with two or more turns per coil can be used. Fig. 13 shows a group of two coils with two turns per coil.

As series windings are preferable for high voltages, parallel windings with more than one turn per coil are not often used, and those with more than two turns are very rare. Series windings are seldom used in machines having ten or more poles.

26. Figs. 14 and 15 illustrate completed armatures, that shown in Fig. 14 having a series winding and that in Fig. 15 a

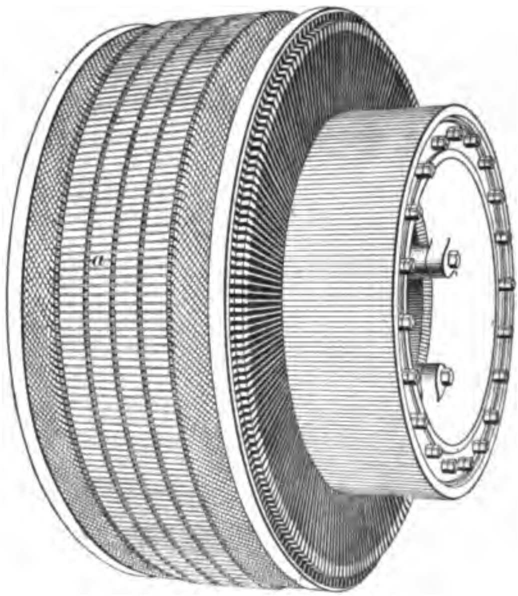


Fig. 14

parallel winding. The two windings can be distinguished by noting the way in which the ends, or leads, of a conductor turn on leaving a slot. In a series winding, the two ends of each conductor turn in opposite directions, and in a parallel winding they turn in the same direction. In Fig. 14 a conductor in slot *a*, for example, turns up at one end of the slot and down at the other; in the parallel winding, Fig. 15, the conductor in

slot *a* turns up at both ends of the slot. When the leads, or end connections, of the slot conductors form one cylindrical surface with the armature core, as in Fig. 15, the name ***barrel winding*** is sometimes applied.

27. Connection diagrams for drum windings are shown in Figs. 16 and 18. Fig. 16 shows the connections of a series-wound armature for a four-pole generator. For sake of simplicity, an armature with only seventeen slots, seventeen coils, and seventeen commutator bars is represented, and the brushes A, A' and B, B' appear to be inside the commutator instead of in their true position outside. Brushes of like polarity are

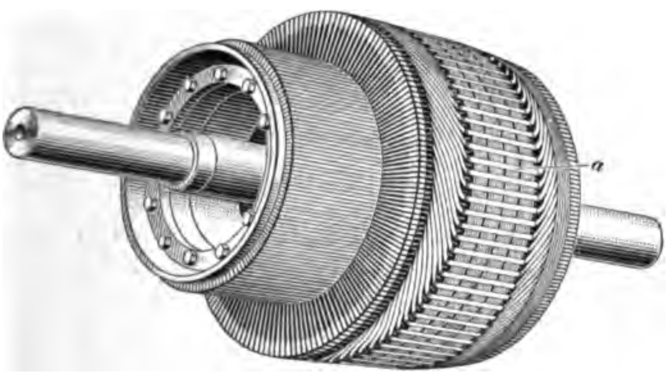


FIG. 15

cross-connected; these cross-connections on a generator are often called *bus-rings*.

The commutator segments *a*, *b*, etc. are connected with the slot conductors *1–1*, *28–28*, *3–3*, *30–30*, etc. by the *coil leads*, full lines representing leads in the upper layer and dotted lines those in the lower layer. Two conductors lie in each slot, as shown in Fig. 17, and the coils are completed by the rear end connections, which are represented by curved lines forming the outer part of the diagram, Fig. 16.

The four poles *N*, *S*, *N*, *S* are represented by dotted outlines, and the armature is assumed to be rotating clockwise, as indicated by the curved arrow across slot *3*. Under these conditions the direction of electromotive force induced in each slot

conductor must be from the front end of the armature toward the rear under north poles, and from rear to front under south poles.

At the instant represented, electricity enters the armature winding by way of brush *B* and commutator segment *e* and

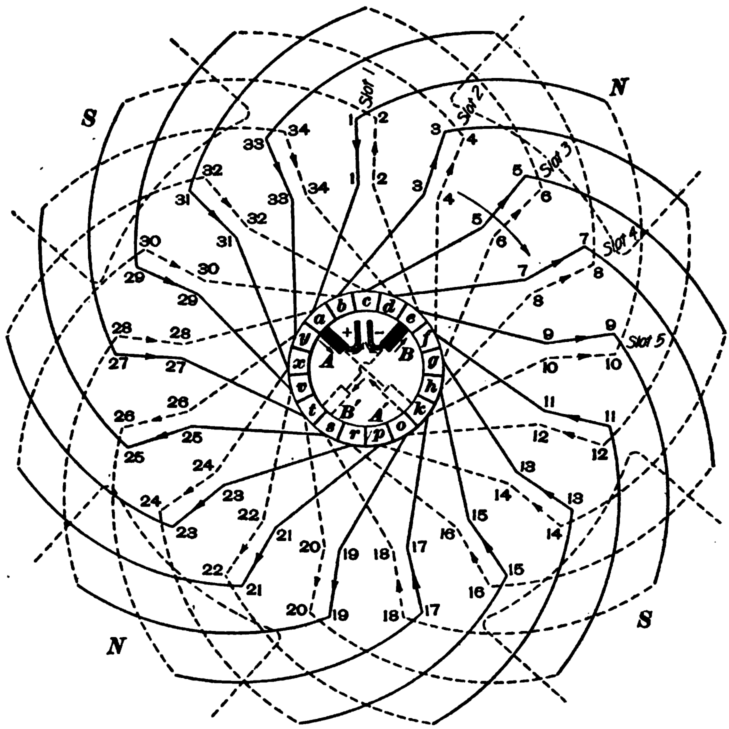


FIG. 16

leaves by way of segment *a* and positive brush *A*. The two paths through the armature are as follows:

1. *e–2–27–t–20–11–f–4–29–v–22–13–g–6–31–x–24–15–h–8–33–y–26–17–k–10–1–a.*

2. *e–9–18–s–25–34–d–7–16–r–23–32–c–5–14–p–21–30–b–3–12 o–19–28–a.*

Only two brushes are needed to make connection with these two paths, but two additional brushes *A'* and *B'* can be used if

desirable, to gain additional brush contact surface without lengthening the commutator. If these additional brushes are used, current can enter path *1* at segments *e* and *t* and leave at segments *k* and *a*; path *2* can be entered at *e* and *s* and leave at *a* and *k*.

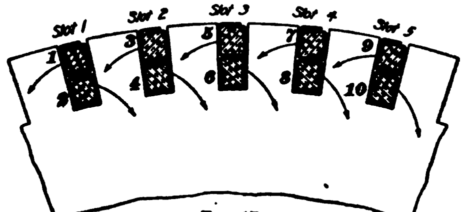


FIG. 17

28. Fig. 18 shows the connections of a parallel-wound armature with seventeen coils, seventeen commutator segments, and seventeen slots. In this case, there must be four brushes in order to make connection with each of the four

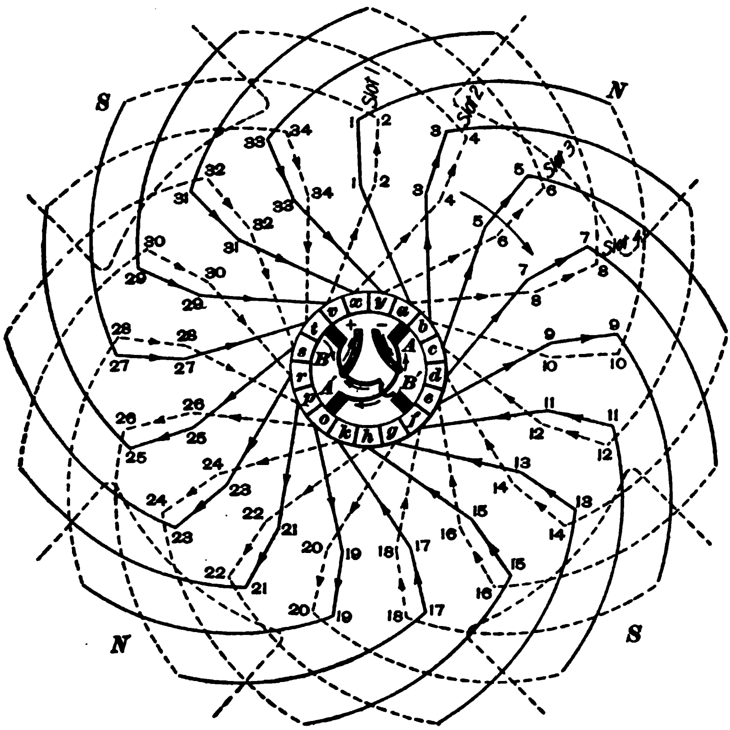


FIG. 18

paths through the armature. At the instant represented, electricity enters the armature by way of commutator segments *a*, *b*, and *o* and leaves by way of segments *f* and *t*. The coil, including conductors *1* and *10*, is short-circuited by brush *A* and therefore carries none of the current of the external circuit; the four paths through the remaining conductors can be traced as follows:

1. *a–8–33–y–6–31–x–4–29–v–2–27–t.*
2. *o–19–28–p–21–30–r–23–32–s–25–34–t.*
3. *b–3–12–c–5–14–d–7–16–e–9–18–f.*
4. *o–26–17–k–24–15–h–22–13–g–20–11–f.*

29. With either type of winding, the direction of current in the circuits remains the same at every instant, but each coil is passed on from one circuit to the next every time the commutator bars with which it is connected pass a brush. For example, in Fig. 16, as soon as segment *d* passes under brush *B*, the direction of current in the coil *d–34–25–s* will be reversed, making it agree with the direction indicated in coil *e–2–27–t*.

30. The coil leads may be of equal length so as to bring the correct position of the brushes opposite the pole centers, as indicated in Figs. 16 and 18, or one lead to each commutator segment may be enough longer than the other to bring the correct brush positions opposite the spaces between poles, the choice depending on which position makes the brushes most accessible. In both cases, the coils short-circuited by the brushes are always in the neutral spaces.

31. The winding shown in Fig. 16 is called **single series.** In addition, another type of series winding, called **double series,** is sometimes used. Double-series windings are not common, however, in modern generators. In such windings, a series of $\frac{P}{2}$ coils ends in a segment next but one to the segment at which it starts. Such a winding is thus in two parts, each connected with alternate commutator segments and each affording two paths for current through the armature. The brushes must be wide enough to make contact with at least

three commutator segments, in order that both windings shall be active.

32. With parallel windings and many poles, commutator bars or slot conductors between which the voltage should be equal at every instant, that is, those exactly two pole pitches apart, are usually **cross-connected** in order to equalize the current in the several paths. Fig. 19 shows a generator armature with seven cross-connecting rings connected with the

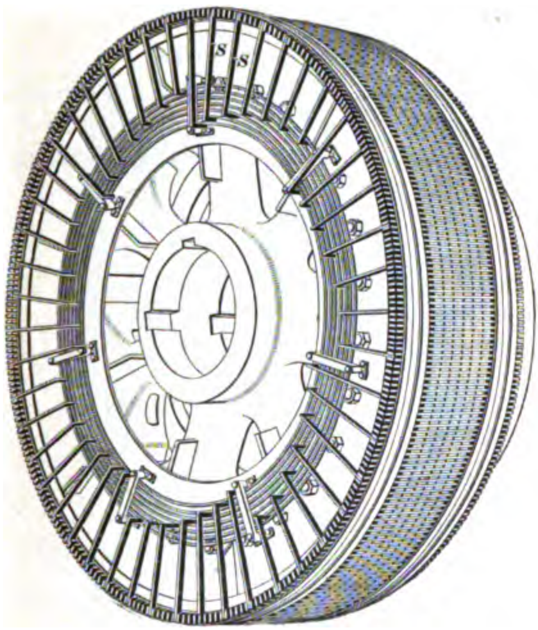


Fig. 19

armature winding by leads S. Each ring must be connected at equally spaced points two pole pitches apart, and as in this case each ring has seven leads, this armature must be for a fourteen-pole machine. The rings are sometimes placed on the commutator end and connected with commutator segments instead of on the rear end as shown.

Without cross-connecting rings, unequal division of current may occur among the several paths; in fact, owing to inequalities

in the reluctances of the magnetic circuits, the voltage developed in the conductors of one path may be enough greater than that developed in other parallel paths to cause large local currents in the armature circuits so that part of the winding acts as a generator and part as a motor. Heavy mechanical stresses are thereby set up in the machine; the manifestations are vibration and trembling of the whole structure, with sparking and flashing at the commutator. Properly connected equalizing rings prevent such disturbances.

FIELD MAGNETS

33. The magnet yoke or field frame of a generator is usually made of soft cast steel, of sheet-steel punchings, or of cast iron. The yoke forms a path between poles for the magnetic flux

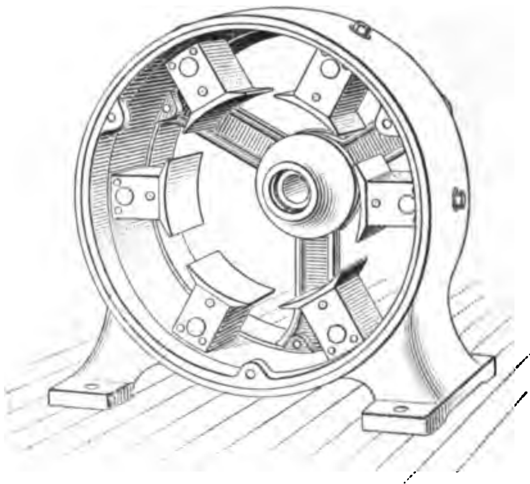


FIG. 20

established by the field coils and also supports the poles and their coils. The yoke is bolted either to a cast-iron base or to a foundation, and it must have suitable feet for its support. Yokes made of punchings are provided with cast-iron or steel clamping rings having feet attached.

The pole pieces, except in very small machines, are made of cast steel or of laminations punched from steel sheets. High

magnetic permeability of materials used for pole pieces permits the use of small pole pieces and, therefore, small field coils. The poles are usually made separate from the yoke and bolted to it, as shown in Fig. 20. The magnet yoke here shown is a soft-steel casting, and the pole pieces are made of steel punchings riveted together. In assembling the machine, the field coils are slipped over the pole pieces and the latter are then bolted to the yoke. If the pole pieces and the yoke are of the same material, they may be made in one piece; if of

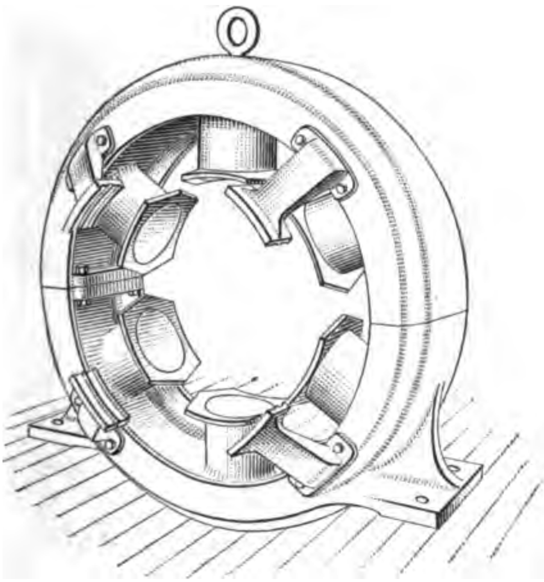


FIG. 21

different materials, the poles are sometimes placed in the mold and the yoke is cast around them, thus forming a solid unit.

Fig. 21 shows a cast-iron magnet yoke with solid-steel poles cast in, and Fig. 22 shows similar construction with laminated poles. In each case, cast-iron collars are provided for the ends of the poles next to the armature in order to retain the field coils and to spread the flux over the armature surface.

The adjoining surfaces of all joints in the magnetic circuit are accurately machined and securely bolted together so as to

make the reluctance of the magnetic circuit as low as possible. Such joints occur between the poles and the yoke in the construction shown in Fig. 20, and between the halves of the yoke in the construction shown in Figs. 21 and 22.

34. The magnetic flux usually passes across the air gap between the armature core and the pole faces in tufts, owing to teeth of the core. The flux follows the teeth to their ends and spreads in traversing the gap. If the length of the air gap measured from the top of the armature teeth to the sur-

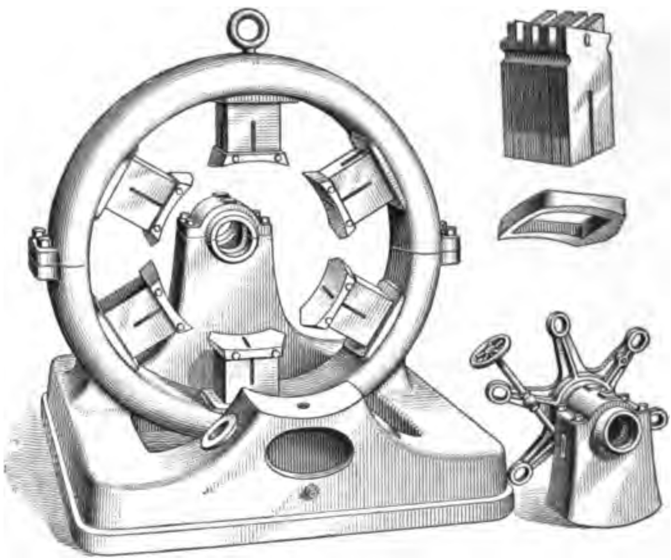


FIG. 22

face of the poles is less than a half of the opening between the tops of the teeth, tufts of magnetism will be effective at the pole faces, and if the faces of the poles are of solid iron or solid steel, eddy currents will be developed as these tufts sweep across them. In such machines, the pole pieces may be advantageously made up of laminations in order to reduce eddy currents. These eddy currents are present only in the pole faces, because in the iron the flux promptly spreads to a uniform density. The pole punchings may be riveted together securely, because

no change of magnetic flux occurs in the body of the pole to cause eddy currents in the rivets. Rivets cannot be used in the armature core, however, because the flux continually changes throughout the core body. In some constructions, laminated pole shoes are bolted to solid poles.

35. Generators may be provided with shunt, series, or compound field windings, but compound windings are most common because they are more suitable for obtaining the constant voltage generally required. Shunt- and series-wound generators are used only for special purposes. Generators with fields excited by current from some external source are also sometimes used; such generators are said to be *separately excited.*

The field coils may be wound on spools, or bobbins, or on a form, and then be bound together securely with tape, rope, or some other insulating material. Shunt coils are practically always composed of cotton-insulated copper wire; series and commutating pole coils also are sometimes made of insulated round wire and sometimes of rectangular copper or sheet-copper strips. Coils of only a few turns each for carrying large currents are sometimes made of cast copper. Shunt field coils and sometimes other coils of fewer turns and larger conductors are frequently insulated by the impregnation process, whereby hot insulating compound is forced into every opening in the coil, where it solidifies, making the coil a solid mass that is impervious to moisture and capable of rapid heat dissipation.

36. Field-coil spools are made with a sheet-metal body, often sheet iron, but with spool heads, or ends, preferably of some non-magnetic material, such as brass, fiber, wood, etc. If the spool heads were made of iron, some magnetic flux would follow them and leak across between the magnet poles instead of following its useful path through the armature. Field coils are sometimes made with ducts or passages through which air can pass. This practice is resorted to in order to obtain lower operating temperature or to permit the use of lighter field coils with a given temperature.

DESIGN FEATURES DETERMINING OUTPUT

DIMENSIONS

37. The product of the number of conductors on the surface of an armature and the number of amperes in each conductor is the number of **ampere-conductors,** and the quotient obtained by dividing this number by the circumference of the armature in inches is the number of **ampere-conductors per inch.**

On any given armature, the number of ampere-conductors is approximately the same whether there are few conductors with large current in each or many conductors each carrying small currents. Thus, an armature may be wound with 200 face conductors capable of carrying 80 amperes each or 400 conductors capable of carrying 40 amperes each or 800 conductors capable of carrying 20 amperes each. In each case, the number of ampere-conductors will be 16,000. If the first winding develops 125 volts, the second winding in the same field and at the same speed will develop 250 volts, and the third 500 volts. The output, or product of volts and amperes, will be the same in each case, 10,000 watts, or 10 kilowatts.

38. Any variation either in the magnetic flux of the field in which an armature rotates or in the speed of the armature changes the rate at which the ampere-conductors cut lines of force and thus varies the voltage and the output. Also, changing the number of ampere-conductors changes the output proportionately.

Increasing the length of an armature increases the space for magnetic flux proportionately, thus affecting the output directly as the change of length; increasing the diameter increases both the space for flux and the space for ampere-conductors, thus affecting the output as the square of the

diameter. Changes in the magnetic density at the armature surface or in the number of ampere-conductors per inch of periphery affect the *activity* of the armature surface.

Let P = output of an armature, in kilowatts;
K = an activity factor, sometimes called an *output constant;*
s = speed of armature, in revolutions per minute;
l = length of armature core, in inches;
d = diameter of armature core, in inches.

Then,
$$P = K\,s\,l\,d^2$$

The formula shows how a change in dimensions affects the output. The factor K is nearly the same for generators of the same output made by different manufacturers. The diameter D is limited by the safe peripheral, or surface, speed, and, therefore, a slow-speed armature, such as is shown in Fig. 2, can have greater diameter than can a high-speed armature like that shown in Fig. 4.

COMMUTATION

ARMATURE REACTION

39. Armature reaction is the name given to the influence that is exercised on the magnetic field by the current in the armature conductors. When electricity is flowing in the windings of a generator armature, all the conductors adjacent to each north pole are carrying current across the armature face in one direction, and all the conductors adjacent to south poles are carrying current in the opposite direction. As the armature rotates, individual conductors are continually passing from the group under one pole into the group under the next pole, but the direction of current in the conductors in each group remains unchanged.

Fig. 23 represents this condition in a four-pole generator. Conductors under north poles are represented as carrying current from the observer, and this current sets up magnetic flux along paths crossing the poles, as indicated by the dotted

lines crossing one north pole. Similar paths, not shown, cross the other poles. The path, *a–b–c–d*, includes all the face conductors of the group; but this route is largely through air and other non-magnetic material, and its reluctance will permit only small flux to be established. The path *e–f–g* surrounds a smaller number of ampere-conductors, but is mostly through iron and therefore carries considerably more flux.

40. The flux established by the armature conductors is useless and often troublesome. The flux along the path *a–b–c–d*, Fig. 23, crosses the armature conductors at the point where the coils of which they are a part are short-circuited by the brushes on the commutator. The resistance of the short-circuited coil is very low, and a little flux in this path may cause the development of enough voltage to establish a large current in the coil. This short circuit current enters the brush at one edge and leaves it at the other, agreeing with the direction of the load current in one edge of the brush and opposing it at the other. The current density in one edge of the brush may therefore become very high, while it is low or even reversed in the other edge. The high density thus caused in the edge of the brush may cause sparking.

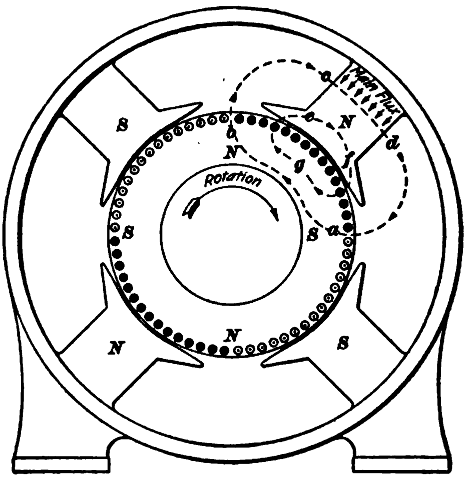


FIG. 23

Furthermore, the flux along the path *e–f–g* agrees in direction with the main flux in one side of the pole face, causing high magnetic density there, and opposes it at the other side, causing low density at that side. This unbalanced magnetic condition may cause unbalanced voltage conditions in the armature coils.

COMMUTATING POLES

41. The undesirable flux in the path *a–b–c–d*, Fig. 23, can be destroyed by means of **commutating poles**, as shown in Fig. 24. These poles make this path almost entirely through iron, and flux may be very readily established along it. The exciting coils, however, on the commutating poles are connected in series with the armature, so that their magnetomotive forces are always proportional and opposed to those of the armature, thus nullifying the effect of armature reaction in this path, so that almost no sparking results at any load. These poles do not, however, prevent the cross-magnetization and field distortion caused by flux in the path *e–f–g*.

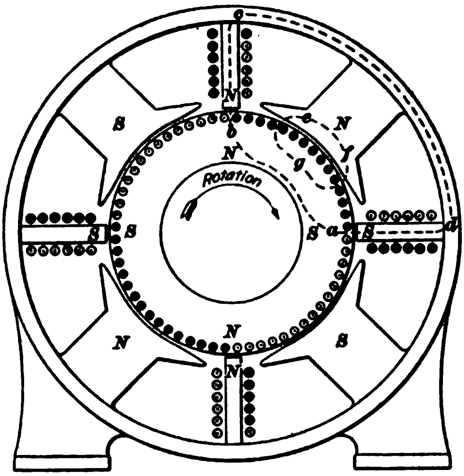


FIG. 24

COMPENSATING POLE-FACE WINDING

42. A **compensating pole-face winding**, as indicated in Fig. 25, arranged in slots in the pole faces and connected in series with the armature can be used not only to overcome the effects of all armature reaction but also to perform the function of a series-field winding in helping to regulate the voltage. The number of these pole-face conductors is chosen so that the number of pole-face ampere-conductors will slightly exceed the number of armature ampere-conductors. The direction of current in the pole-face conductors opposes the direction of current in the adjacent armature conductors; consequently, no undesirable fluxes can be established by the

armature ampere-conductors in either of the paths *a–b–c–d* or *e–f–g*.

43. The field structure for a generator with compensating pole-face winding is shown in Fig. 26. For this particular generator, the magnet yoke is made of sheet-steel punchings bolted between heavy cast-iron flanges with supporting feet *a*. Each pole piece consists of two parts, a magnet core *b* and a pole face, or shoe, *c*, each built separately of punchings riveted together. Long bolts passing through the yoke and magnet cores screw into the pole shoes and hold the pole and its shoe securely in place in the yoke. Between every pair of pole shoes is a commutating pole *d* built up of punchings, riveted together and held in place by brass keys driven in between the commutating poles and the adjacent pole shoes, so that these poles are not attached to the yoke. The magnet yoke, the commutating poles, and the pole shoes are assembled with air vents, or flues, at intervals, as can be seen on the pole faces, in much the same way as armature cores are constructed.

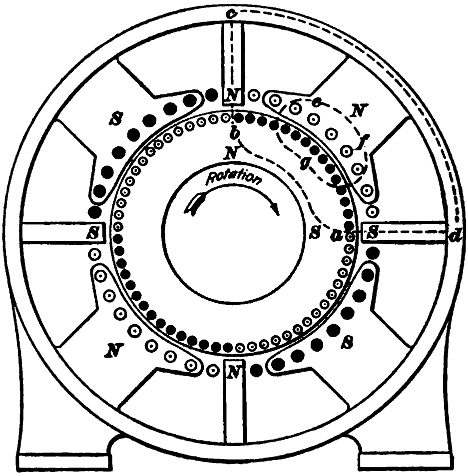


FIG. 25

The commutating poles are shaped to permit some leakage flux between adjacent poles and to pass enough of this flux across the air gap between the poles and the armature to provide a good commutating field for the brushes. Each pole shoe *c* has three slots, and the spaces beside the commutating pole form two more, making five slots per pole for compensating windings.

44. Fig. 27 shows the complete field magnet with shunt field coils at *a* and compensating coils at *b*, each occupying only four of the five available slots. The space on one side of the commutating pole is left vacant, as shown at *c*. Each compensating coil therefore occupies two slots in one pole shoe,

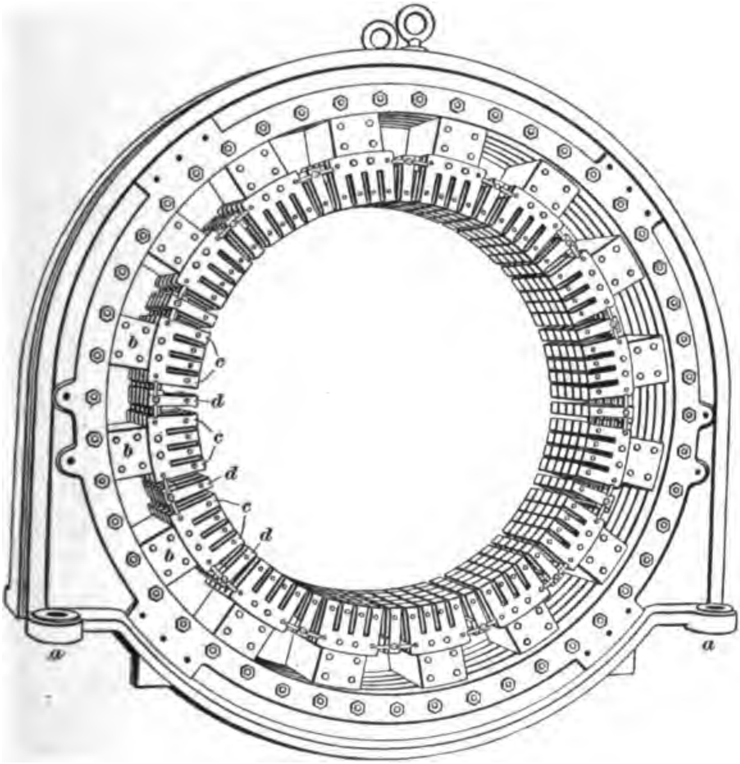


FIG. 26

one in an adjacent shoe, and a slot space at one side of a compensating pole. This position enables these coils to increase the flux through the armature as the current through them increases, and thus cause the generator to *overcompound;* that is, the generator voltage can be made to rise as the load increases, thus compensating for increased voltage drop in the lines leading to distant lamps or other electric devices.

UNIPOLAR GENERATOR

45. Some attempts have been made to avoid commutation entirely by arranging a magnetic field so that the armature

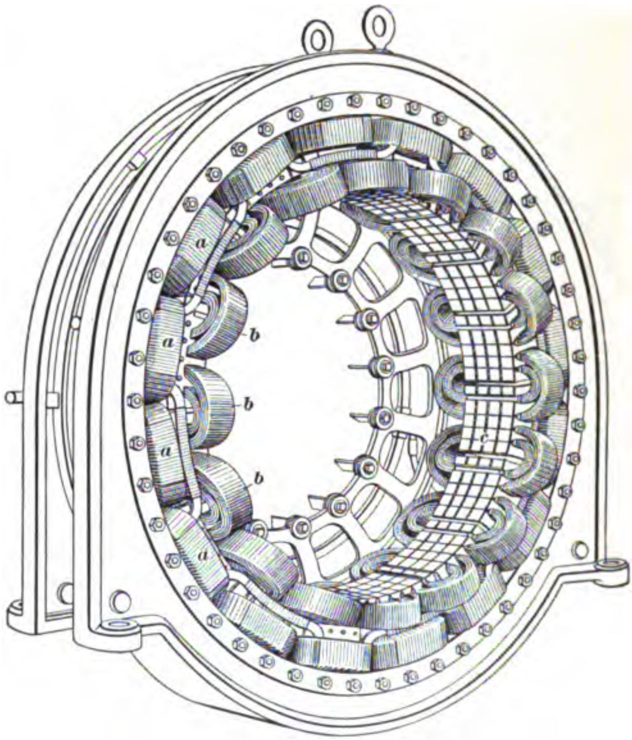
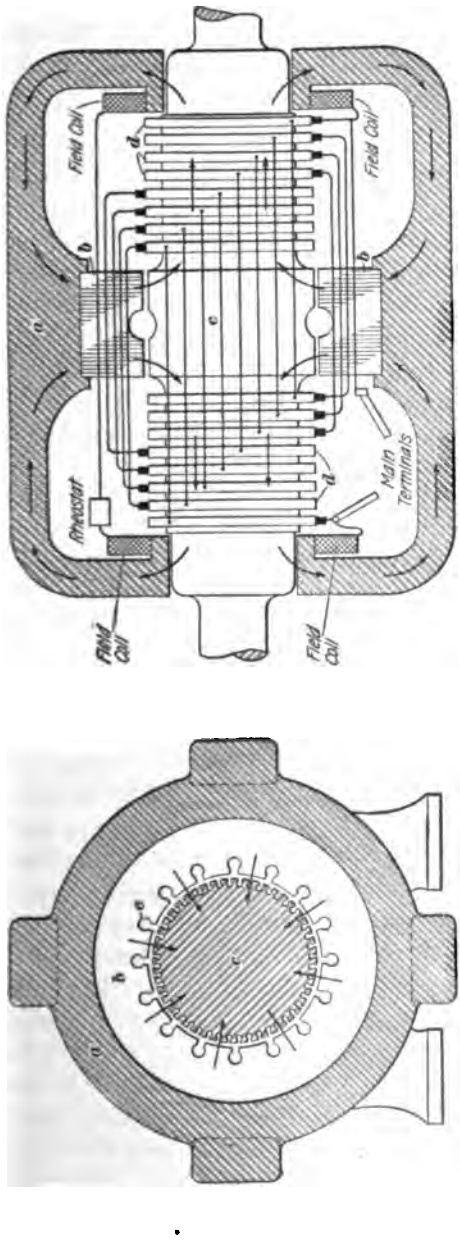


FIG. 27

conductors cut lines of force in only one direction. Such a machine is variously called *unipolar*, *homopolar*, and *acyclic*.

Fig. 28 shows sections (*a*) and (*b*) of a unipolar generator; many of the parts to which reference will be made can be seen in both views. The frame, or magnet yoke, *a* is a steel casting that carries a laminated pole-face ring *b*. The armature core *c* is a steel forging, and the conductors are carried in slots in its periphery. These conductors terminate in collector rings *d* at each end of the armature. The collector rings slide under



(b)

(a)

Fig. 28

stationary brushes, which are interconnected by return conductors carried in slots *e* in the pole face. A shunt field coil concentric with the armature is carried on an inward projection of the field frame at each end of the armature core, as shown in view (*b*). The leads of the return conductors between the rings are offset, or advanced, enough to carry the armature current around the magnetic path and thus cause compounding as well as prevent armature reaction.

46. The path of the magnetic flux is indicated by the arrows in both views of Fig. 28. Lines of force enter the armature from all directions around the pole face, pass lengthwise of the armature core through the field coils, and return

through the magnet frame to the pole face. As the lines of force are cut in only one direction, voltage is developed in the same direction in all armature conductors, and these conductors are so interconnected that their voltages are added to give the required voltage at the machine terminals.

47. The chief advantage of unipolar generators is the avoidance of commutator troubles; but the practical elimination of these troubles by commutating poles and compensating field windings, together with the complications of the unipolar generator, make the commutator type of machine preferable. The only possible field for the unipolar machine is for high-speed, high-current, low-voltage generation, and their practicability even here is doubtful. The sectional views, Fig. 28, were made from drawings for a 260-volt, 7,700-ampere generator to operate at 1,200 revolutions per minute.

ADAPTATION TO SERVICE CONDITIONS

THREE-WIRE SYSTEMS

THREE-WIRE GENERATORS

48. A three-wire system of circuits employs the usual positive and negative conductors, here called **main,** or **outside, wires,** and an additional conductor called the **neutral wire,** or simply the *neutral*. The voltage between the neutral and either outside wire is one-half of the voltage between the two outside conductors. The circuit between the positive main and the neutral is called the *positive side* of the system, and the circuit between the neutral and the negative main, the *negative side* of the system.

The voltages usually employed are 220–250 between the outside wires and 110–125 between the neutral and either outside wire. Motors are operated between the outside wires, and lamps between the neutral and either outside wire. Electricity

can thereby be transmitted at higher voltage than that at which much of it is used, thus effecting a saving of copper.

49. In order to operate a three-wire system successfully, the voltages on the two sides must be kept balanced, or equal. As lamps are switched on and off, the loads on the two sides become unequal, and devices must be employed to compensate for these inequalities in order to keep the voltages equal. The early method was to connect two 125-volt generators in series between the outside wires and to connect the neutral wire to the circuit between the two generators. But an ordinary two-wire generator that develops the voltage required between the outside wires can be equipped with auxiliary parts by means of which a neutral, or middle, voltage can be obtained, making the machine a **three-wire generator**.

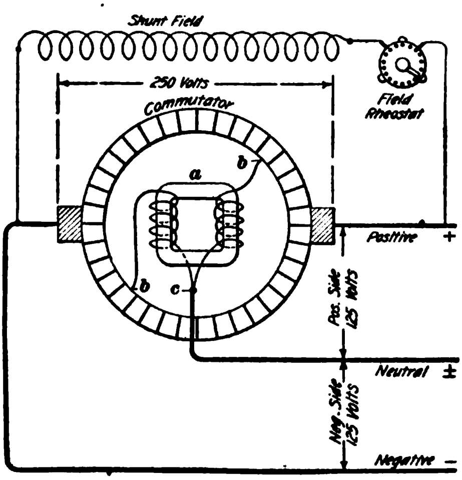


FIG. 29

50. Fig. 29 shows a diagram that will assist in making clear the operation of a three-wire generator. A **compensating transformer** *a*, sometimes called a *three-wire compensator*, or *balance coil*, is shown connected between two diametrically opposite bars *b* of the commutator of a two-pole generator. The middle point of the transformer winding is also connected with the neutral wire. The transformer may or may not rotate with the armature. If it rotates, the connection at *c*, joining the neutral wire with the transformer, must be through sliding contacts consisting of a rotating slip ring on which slides a stationary brush. The transformer is then connected with the slip ring and the neutral wire with the brush. If the transformer is stationary, no slip ring is necessary for the

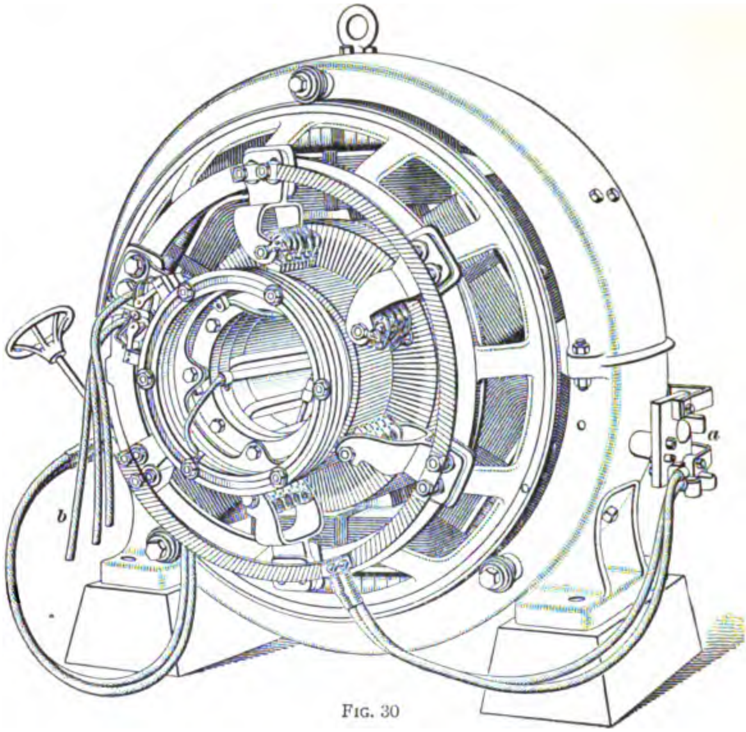


FIG. 30

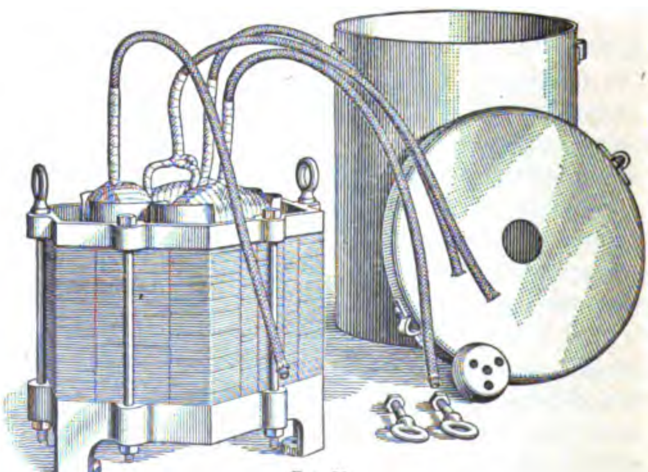


FIG. 31

contact *c*, but two slip rings must be used between the bars *b* and the transformer. The bars are then connected with the rings, which rotate with the commutator, and the transformer leads are connected with the stationary brushes sliding on the rings.

In either case, the transformer remains connected with two bars *b* and with the neutral wire. As the armature rotates, the voltage across the transformer varies from the full voltage of the generator when the bars *b* are under the brushes to zero voltage when these bars are midway between the brushes. The neutral wire, being connected with the middle point of the transformer winding, is always at a potential approximately midway between the potentials of the two brushes or the two outside wires. If the difference of potential between the brushes is 250 volts, the difference of potential between either outside wire and the neutral wire is approximately 125 volts.

51. If the low-voltage devices are so distributed between the two sides of a three-wire system that the number of amperes is the same on both sides, the system is said to be *balanced*, and the neutral wire carries no current to the generator or from it. If the load on the positive side exceeds the load on the negative side the positive wire carries more current than the negative wire and the neutral carries the difference toward the generator. If the negative side has the greater load, the negative wire carries the greater current and the neutral carries the difference from the generator. The neutral current may therefore vary from zero to the full unbalanced current, and its direction may be either toward or away from the generator.

52. Fig. 30 shows a multipolar, compound-wound, engine-type, three-wire generator with three slip rings mounted at the outer end of the commutator. These rings are permanently connected with commutator bars located 120 electrical degrees apart. At *a* is one of two terminal boards attached to the generator frame, the other being near the hand wheel on the opposite side. The three leads *b* are for connection with three of the compensator leads. The compensator is shown removed

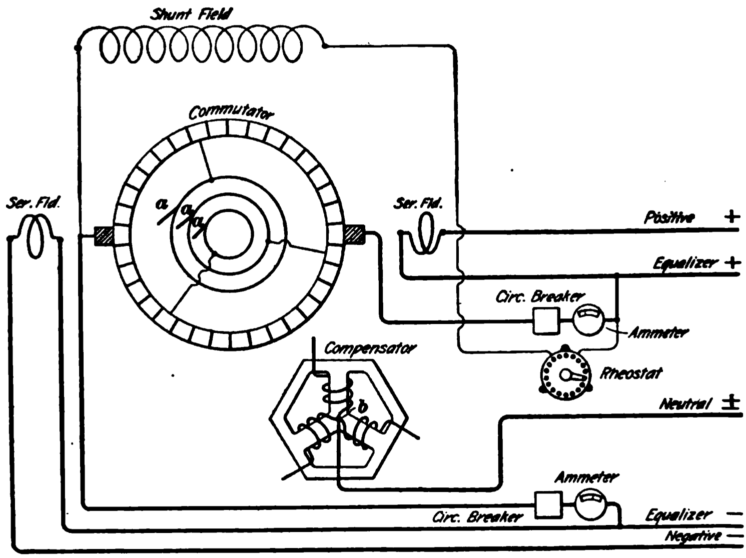

Shunt Field
Commutator
Ser. Fld.
Ser. Fld.
Positive +
Equalizer +
Circ. Breaker
Ammeter
Rheostat
Compensator
Neutral ±
Ammeter
Circ. Breaker
Equalizer −
Negative −

FIG. 32

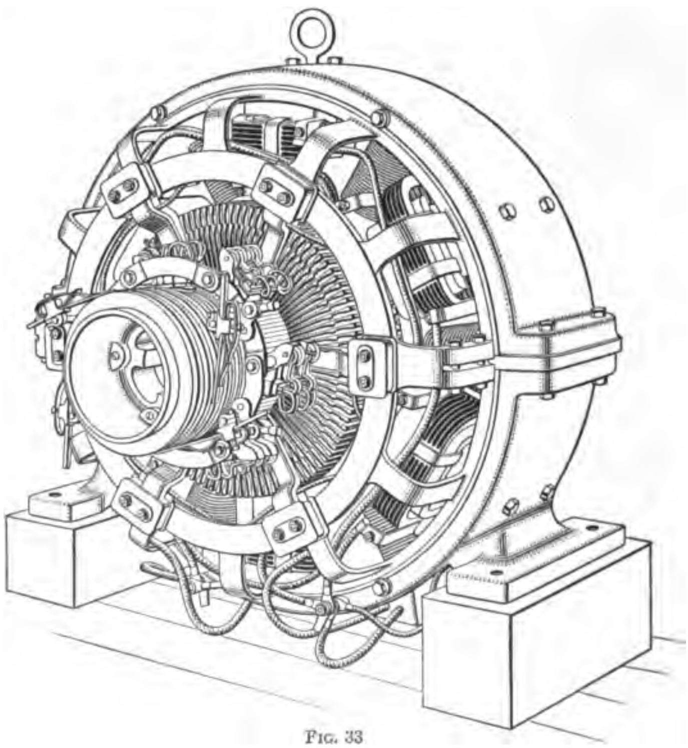


FIG. 33

from its case in Fig. 31, and in Fig. 32 is shown a diagram of connections, in which, for sake of simplicity, the generator is represented as bipolar. Three of the compensator leads are for connection with the three brushes *a* on the collector rings, and the fourth, from the neutral point *b*, is for the neutral wire. The circuit-breakers, the ammeters, and the field rheostat are shown compactly arranged, as on a switchboard, with the neces-

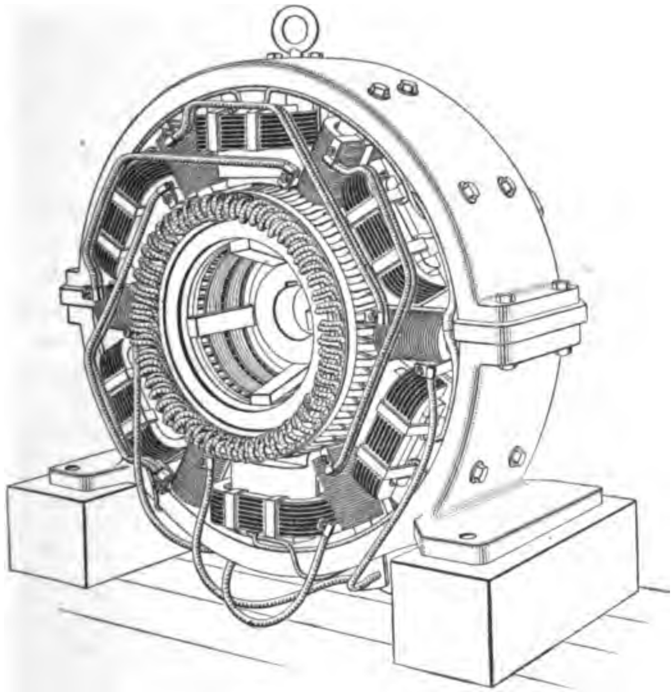


FIG. 34

sary leads from the generator. A **circuit-breaker** is a device for automatically opening a circuit when the current becomes too large, and an **ammeter** is a device for indicating the strength of current. One of each of these instruments is connected in each outside wire.

If this machine is used in parallel with others, equalizer connections are needed to make each machine carry its share of the load. The connection of an equalizer with one terminal of each

series field is shown; these conductors extend only between the machines operating together. Equalizer connections will be explained in another Section.

53. Figs. 33 and 34 are front and rear views of a four-ring three-wire compound-wound generator equipped with commutating poles. Both the series coils and the commutating-pole coils are arranged in two groups each, with alternate coils in each group. The current in each main wire must therefore pass through half the series coils and half the commutating-pole coils. The cross connections between coils are plainly shown in the two views. Fig. 35 shows one of the two balance coils used with such a machine.

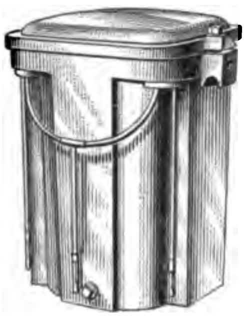


FIG. 35

The diagram of connections is shown in Fig. 36, a two-pole machine being represented because it is more simple and equally representative of the principles. The leads of the two compensators are connected with the brushes *a* and *b*, as indicated by the reference letters, so that each compensator is connected across points on the commutator one pole pitch apart. Both neutral leads from the two compensators are joined to the neutral line wire.

54. Fig. 37 shows a type of armature that includes a compensator, thus necessitating only one slip ring and simplifying the connections. The compensator is built in the form of a ring, which revolves with the armature; connections between the compensator and the armature winding are made direct at *a* and *b*. The collector ring is mounted on the commutator end of the machine, not shown.

55. In another type of three-wire generator, the neutral voltage is obtained by means of an auxiliary winding, usually placed in the bottoms of the armature slots under the main winding. The neutral wire is connected with the neutral point of the auxiliary winding by means of a slip ring, and this winding

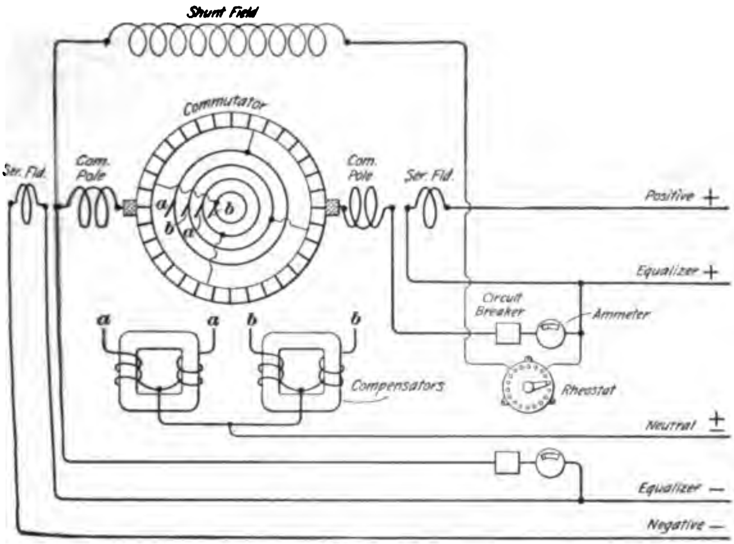

Shunt Field
Commutator
Ser. Fld.
Com. Pole
Com. Pole
Ser. Fld.
a
b
b
a
Positive +
Equalizer +
Circuit Breaker
Ammeter
a
a
b
b
Compensators
Rheostat
Neutral ±
Equalizer −
Negative −

Fig. 36

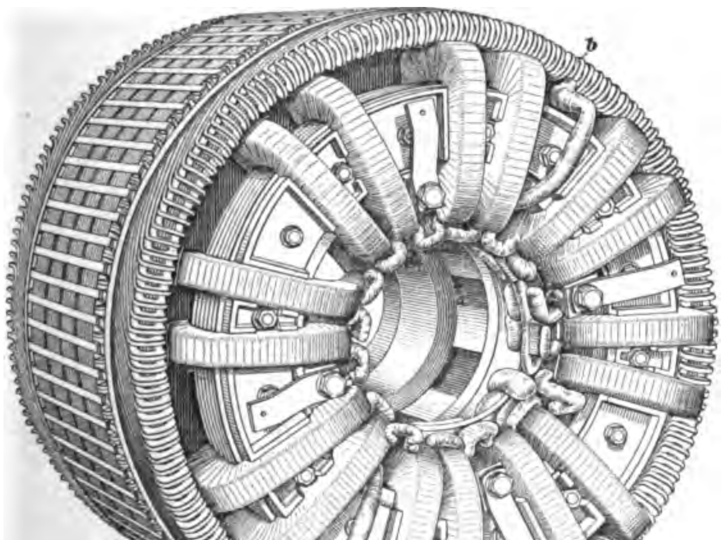

b
a

Fig. 37

is joined to the main winding at the proper points. Such a generator appears much like an ordinary two-wire machine, except that the connections are more complicated.

56. Three-wire generators are usually guaranteed to keep the difference between the voltages on the two sides of the system within 2 per cent. of the line voltage with any current in the neutral wire up to 25 per cent. of full-load current. For example, if the full-load current of a 250-volt three-wire generator is 400 amperes, the difference between the voltages on the two sides of the system will not exceed 5 volts (.02×250) when the neutral wire is carrying 100 amperes (.25×400); that is, the voltage on the heavy-loaded side will not be less than 122½, and on the light-loaded side not over 127½. Closer regulation is sometimes obtained by arranging the circuits so that a switchboard attendant can transfer circuits from one side of the system to the other when necessary to improve the balancing.

Direct-current generators are usually made so that they can be furnished either with or without three-wire parts. The operation—that is, commutation, heating, and voltage regulation—is practically the same in either case, provided the unbalanced load is not greater than 25 per cent. of the full load.

THREE-WIRE BALANCERS

57. A **three-wire balancer** is a combination of two compound-wound, two-wire generators, exactly alike, with shafts coupled or continuous, so that the armatures must run together, the general appearance being as shown in Fig. 38. These generators are comparatively small, and the set is used in connection with a larger two-wire generator to supply a three-wire system, the connections being as shown in Fig. 39. The armatures and series fields of the balancer are connected in series across the terminals of the main generator, and the neutral wire is connected to the circuit between the two armatures. Each armature develops approximately one-half as much voltage as the main generator. For example, if the main generator

develops 250 volts, the balancer armatures run as motors at a speed such that each develops a counter electromotive force of nearly 125 volts at no load.

58. The no-load current through the balancer armatures is very small, being only enough to supply their friction and iron losses, and these losses remain practically the same at all loads. The conditions when the neutral wire is carrying current may be explained by reference to Fig. 40. Assume that the positive lead of the three-wire system is carrying 500 amperes and the negative lead 400 amperes, while 100 amperes returns in the neutral wire. The neutral current divides between the

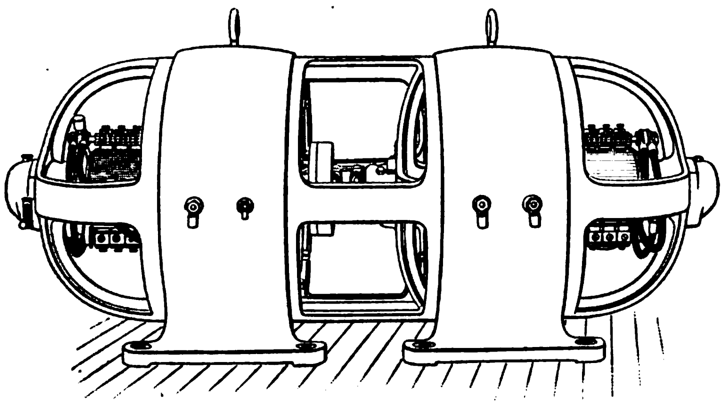


FIG. 38

two armatures of the balancer, driving the one on the lightly loaded side as a motor and passing through the other as a generator. The direction of current in the armature acting as a motor is always from positive to negative, while in the generator armature the direction is from negative to positive.

The motor armature must take enough more than half the current, to supply the losses of both armatures, which for the purpose of illustration, may be assumed to require 5 amperes each. The 100 amperes in the neutral wire must therefore divide so that the motor current is at least 10 amperes greater than the generator current, making 55 amperes in the motor and 45 amperes in the generator. The full-load losses in the

armatures and series fields, which were not considered in the assumed losses, may increase this difference between the motor current and the generator current somewhat. The current in the main generator will be approximately 455 amperes.

59. If the conditions in the three-wire system change so that the heavy load, 500 amperes, is on the negative side, as shown in Fig. 41, then 400 amperes must go out in the positive wire and 100 in the neutral wire. The balancer armature on the positive side must now act as a motor, because the direction of current through it is from positive to negative. The other armature acts as a generator because the direction of current through it is from negative to positive. The current in the main generator is still 455 amperes, of which 55 amperes goes through the motor armature and the balance to the three-wire system. Of the 500 amperes returning in the three-wire system, 45 amperes go through the generator armature and the balance returns to the main generator.

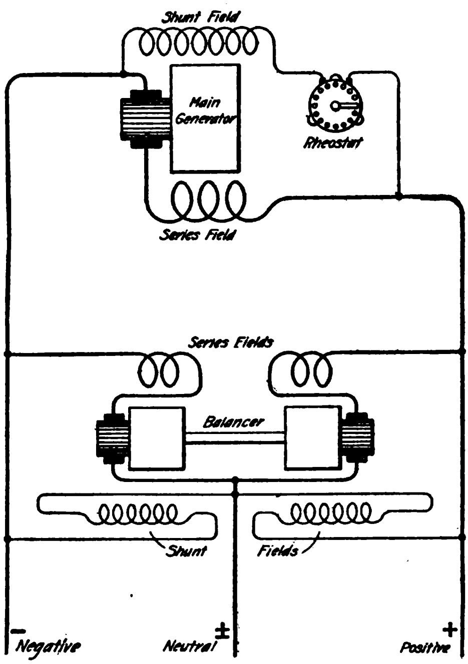


FIG. 39

60. The series fields of the balancer cause a slight rise of voltage on the heavily loaded side, the precise condition desirable for good balance. The shunt and series fields are so connected that their magnetomotive forces are always in the same direction on the generator and in opposite directions on the

motor, as indicated in both Figs. 40 and 41. The effects of the series winding are therefore to increase the field strength of the

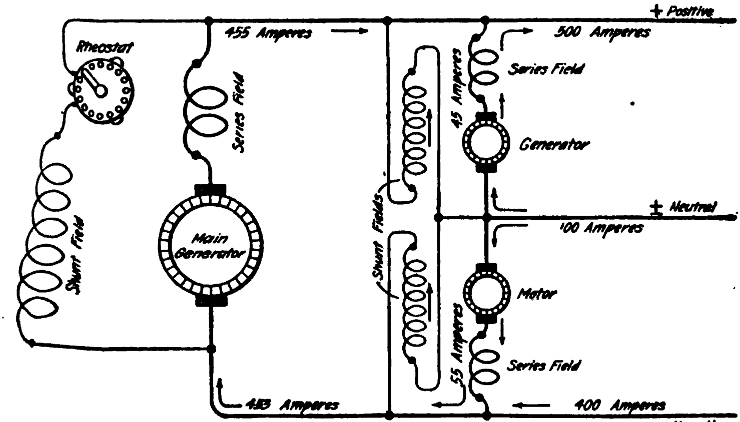


FIG. 40

generator and to increase the speed of the set by weakening the motor field, both of which effects increase the voltage of the generator. A comparatively small series winding therefore produces the desired effect.

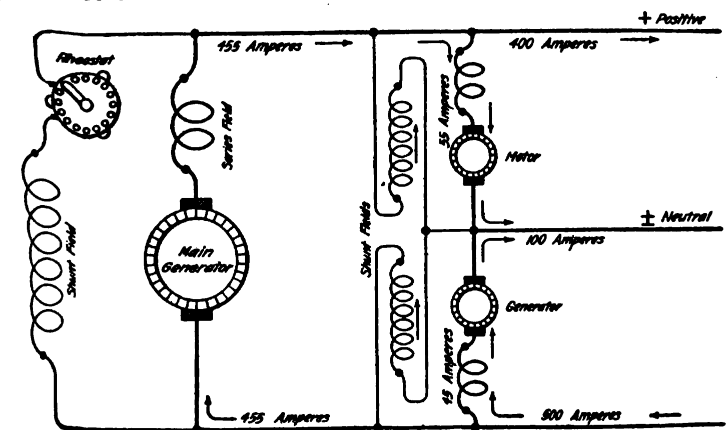


FIG. 41

61. A balancer set can be made to maintain the voltages of a three-wire system within 1 per cent. of equality with 25

per cent. unbalanced load; that is, if a perfect balance is 125 volts on each side, the difference between the voltages of the two sides will not exceed 1.25 volts. In order to obtain such close regulation, however, some additional refinements of connections are essential. One is to arrange the shunt fields so that each is connected across the armature of the other machine, as shown in Fig. 42. If the voltage of either machine rises, it strengthens the shunt

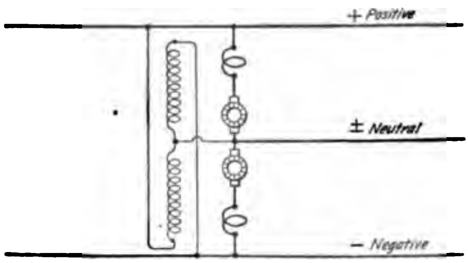


FIG. 42

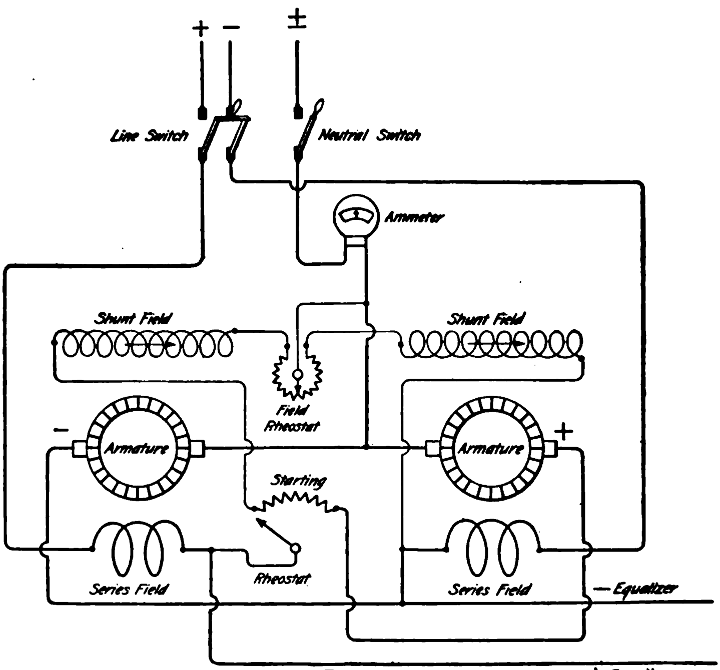


FIG. 43

field of the other machine, while its own field is excited proportionally to the lower voltage, thus equalizing the two voltages.

62. Another refinement is to interchange the series field connections also, as in Fig. 43, so that each armature is in circuit with the series field of the other. The machine acting as a generator then carries in its series field the motor current, which is greater than the generator current, as explained in Art. 58, thus causing increased compounding effect. On the other hand, the series field of the motor carries the generator current, which, being less than the motor current, causes less speed increase with load.

Fig. 43 also shows a field rheostat so arranged as to weaken one field and strengthen the other simultaneously; this is a good plan and is frequently followed, although a separate rheostat can be used in each shunt-field circuit. A starting rheostat, as shown, is practically always necessary. If two or more such sets are used in parallel, equalizer connections are required between the series fields to insure proper division of current among the sets. An ammeter with its zero reading in the center of the scale is shown in the neutral circuit; the direction of current in the neutral is indicated by the direction in which the needle is deflected, and the strength of current by the extent of the deflection.

MISCELLANEOUS THREE-WIRE BALANCING DEVICES

63. Three-Wire Motor With Booster.—Fig. 44 shows the connections of a balancing device consisting of a three-wire machine that operates as a motor driving as a part of its load a small series-wound generator used to raise, or boost, the voltage. A compensator is connected between the booster and the motor. The neutral circuit is thus through the slip rings, the compensator, and the booster. The direction of the booster voltage therefore depends on the direction of current in the neutral circuit, and the number of volts developed by the booster, seldom more than 5, depends on the strength of this current. A small voltage is thus added to the heavily loaded side of the system, maintaining a balance practically as good as is obtained with the balancer sets previously described. A motor regularly employed for driving other machinery can be equipped for driving a booster in this way.

64. Dynamotor With Booster.—Dynamotors are described later. Briefly, a *dynamotor* is a direct-current machine combining both motor and generator action in one magnetic field, either with two armatures or with one armature having two separate windings and independent commutators. Fig. 45 shows the connections of such a machine with a series-wound booster for balancing a three-wire system. The two armature windings of the dynamotor are connected in series across the outside wires, and the booster is in series with the neutral circuit, which is connected with the dynamotor circuit at a point between the two windings. The booster is direct driven by the dynamotor and serves to increase the voltage of the heavily loaded side of the system enough to compensate for voltage drop, thus maintaining good balance.

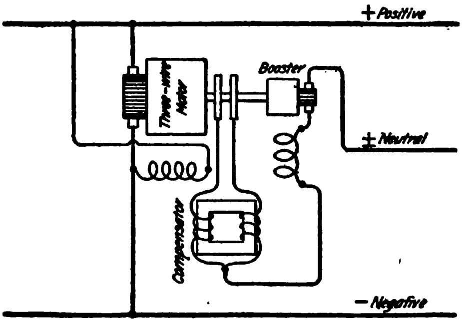


FIG. 44

The two armature windings in the dynamotor are alike, and when the system is perfectly balanced the voltages on the two sides are equal. When the system is unbalanced, the dynamotor winding on the loaded side acts as a generator and the voltage at its terminals falls, owing to the voltage drop in both windings, as is explained later. The voltage of the booster, however, varies with the neutral current in such a way as to keep the two sides of the system at nearly equal voltage.

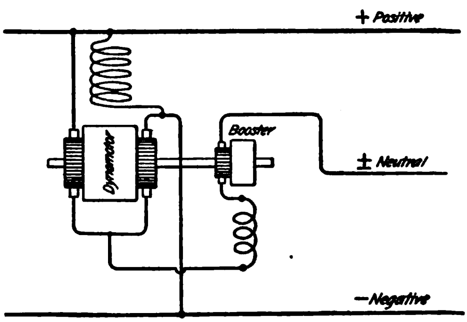


FIG. 45

MOTOR GENERATORS AND DYNAMOTORS

65. A **motor generator** is a combination of a motor mechanically coupled to one or more generators. The form of electrical energy delivered by the generator may be entirely different from that received by the motor. Fig. 46 shows a motor generator consisting of an alternating-current motor and a direct-current generator. The shaft of this set is con-

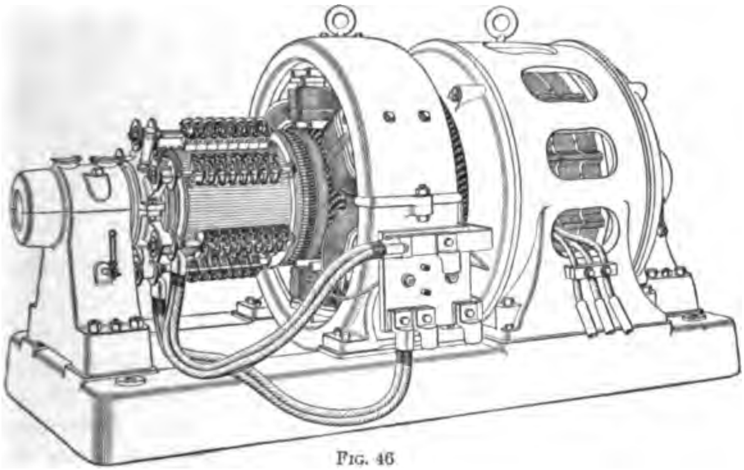


FIG. 46

tinuous and is supported by only two bearings, thus necessitating a shaft of large diameter to obtain the requisite stiffness.

Fig. 47 shows a 240-volt direct-current motor, on the right, coupled to a 30-volt direct-current generator. The two machines have separate shafts and bearings, and the coupling is flexible. This generator supplies current for a telephone system, and in order to avoid a disagreeable humming noise in the telephone instruments, the armature core is smooth, that is, it has no slots; the commutator also has a large number of segments, so as to obtain smooth, steady current. The presence of slots and teeth or the use of a small number of commutator bars would cause enough variation of current to be objectionable in telephone circuits on account of noise in the receivers.

66. Fig. 48 shows the connections of a motor generator consisting of a 125-volt motor and a 40-volt generator, both for

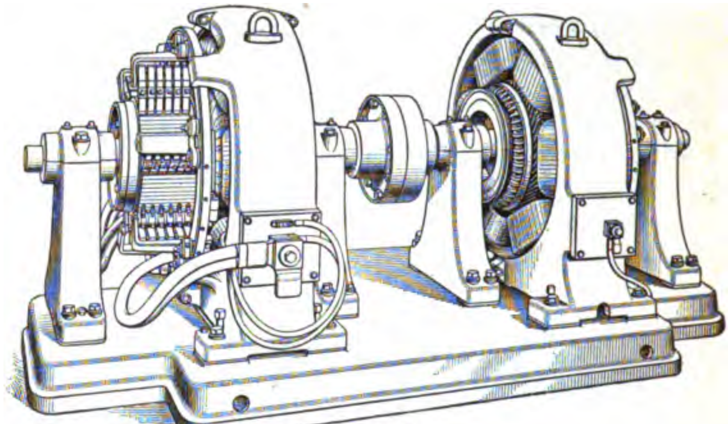


FIG. 47

direct current and shunt-wound. This set is arranged for boosting voltage from 125 to 165.

By reversing the armature connections of the 40-volt machine, its voltage would oppose that of the 125-volt machine and would be deducted from it, leaving 85 volts on the circuit instead of the 165 volts shown in Fig. 48. When current at 85 volts is required and only a 125-volt circuit is available, the reduced voltage can be obtained in this way more economically than to operate a motor generator with an 85-volt generator.

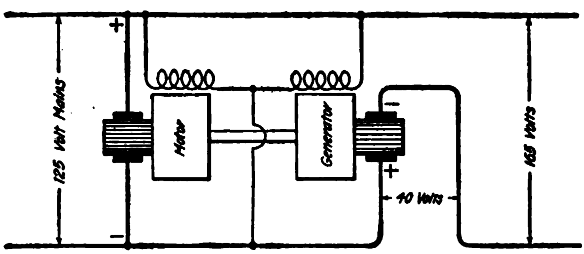


FIG. 48

67. Dynamotors.—Fig. 49 shows one type of dynamotor with the doors opened to give access to the commutator and the brushes. The motor, or primary, winding of a dynamotor is

always designed for the voltage of the circuit from which the machine is to receive energy; the generator, or secondary, winding can be designed to develop any voltage required with a given load. This voltage varies widely as the load changes and cannot be adjusted by regulating the field current, because both windings rotate in the same field and are affected alike by changes in the flux.

The voltage generated in the secondary winding bears a fixed ratio to the counter voltage of the primary winding. This

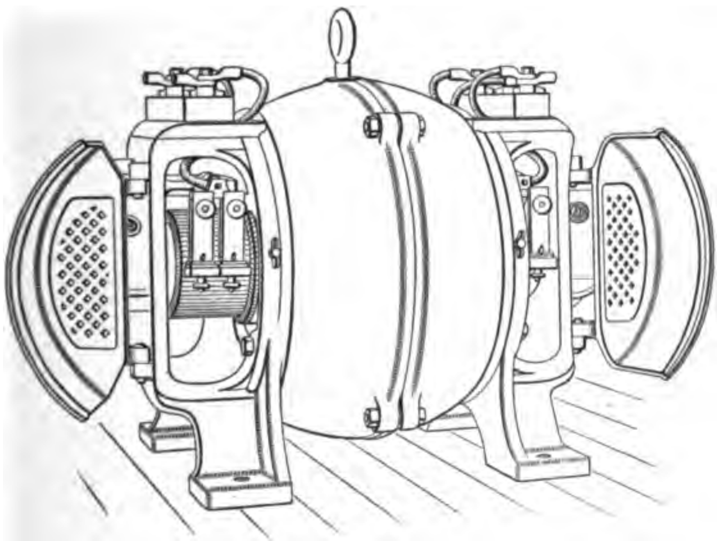


FIG. 49

counter voltage is less than the voltage of the supply circuit by the voltage drop in the primary winding, and the voltage at the terminals of the secondary winding is less than the generated voltage by the voltage drop in the secondary winding. Every change of current in the secondary winding causes a corresponding change of current in the primary winding, and the voltage at the terminals of the secondary winding is affected by the voltage drop in both windings. Dynamotors are used only in small capacities for operating devices on independent circuits, as large call-bell systems.

ELECTROPLATING GENERATORS

68. For electroplating and electrotyping, large currents at about 6 or 12 volts are used, and special generators, often called **electrolytic generators,** are essential for such outputs. The armature conductors must be large, so as to carry the current, and their number must be few, in order to generate the low voltage. The commutator segments must be correspondingly large for the same reason. As a set of brushes can be used for every pole, and since large brush capacity is essential, the number of poles of low-voltage generators is often greater than on generators for the same outputs at higher voltages.

Fig. 50 shows an electroplating generator with two commutators, two separate 6-volt windings, and a terminal board

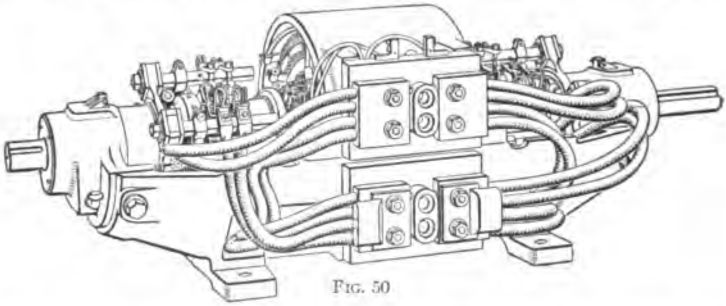


FIG. 50

so arranged that the windings can be connected in parallel for 6 volts or in series for 12 volts. The machine can also be connected with two separate 6-volt circuits. Electrolytic generators are provided with low-resistance brushes of metal or a combination of metal and graphite.

CONSTANT-CURRENT GENERATORS

69. City streets and the interiors of large buildings were formerly lighted by arc lamps connected in series and requiring direct current at some constant value, usually between the limits of 6 and 10 amperes. A special type of generator was used, and some of these generators are still operating. Each

lamp requires about 50 volts, and the machine must be capable of varying its voltage automatically, so as to keep the current constant as lamps are switched in or out of circuit.

70. Fig. 51 shows one type of large constant-current arc-light generator formerly much used. The field has eight coils

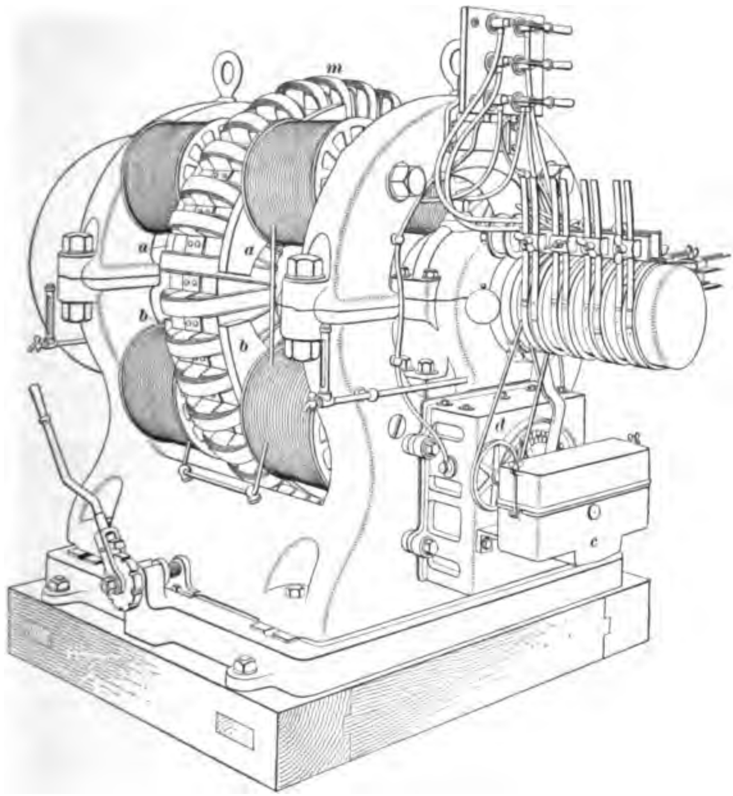


Fig. 51

so placed as to form four magnetic poles. Each pole has two shoes, as at *a* or at *b*, on opposite sides of the armature *m*. The armature is ring-wound and has thirty-two equally spaced coils, as shown in the diagram, Fig. 52. These coils are connected in four equal divisions, each connected with a section of the commutator on one end of the shaft. The connections of only one

section are shown; coils *a*, *b*, *c*, and *d* are in series between segments *j* and *l*, and coils *e*, *f*, *g*, and *h* in series between segments *n* and *p*. Segments *j* and *k* are interconnected; so also are *l* and *m*, *n* and *o*, and *p* and *q*. The direction of rotation is assumed to be counter-clockwise, as is indicated by the curved arrows above and below coil *a*.

At the instant represented, brushes *r* and *t* touch segments *n* and *q*, thus connecting coils *e*, *f*, *g*, and *h* in series between the

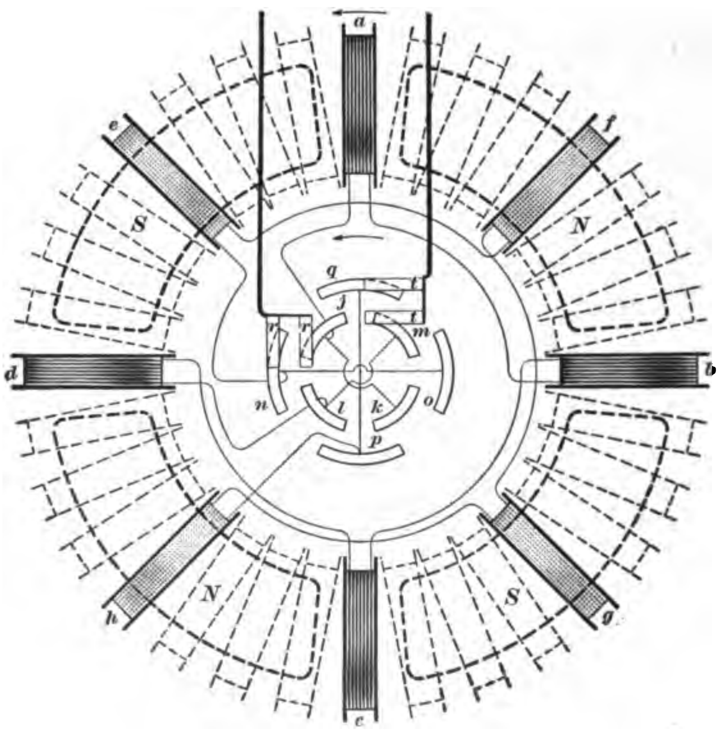


FIG. 52

terminals. These coils are now opposite pole faces, represented by dotted outlines, and are generating electromotive force. Coils *a*, *b*, *c*, and *d* are opposite spaces between pole faces, and are therefore inactive at the instant shown. As these coils pass in front of poles, their segments *j* and *m* will slide under

brushes *r* and *t*. Other coils are similarly connected with other sections of the commutator, and the four sections are so interconnected that the active coils are always in series.

71. These machines are series-wound and are so designed that armature reaction has a comparatively large influence on the field. An increase of armature current therefore distorts and weakens the field, thus tending to keep the current constant. At the same time, an automatic regulator *c*, Fig. 51, adjusts a rheostat *d* and shifts the brushes. The rheostat is in shunt with the series field and is adjusted to divert some of the series-field current and thus weaken the flux on increase of armature current; at the same time, the brushes move to the position for best commutation. The regulator contains an oil pump that operates continuously while the machine is running, and also a magnetically operated valve. When the armature current is at the desired value, the valve remains in a position to allow the stream of oil to discharge into the reservoir without affecting the regulator. If the current changes, the valve moves so that the oil is directed against one side or the other of a vane, so as to turn the regulator and shift the brushes in the direction necessary to restore the current to the desired value.

DIRECT-CURRENT VOLTAGE REGULATION

72. The simplest means of keeping the voltage of direct-current circuits approximately constant with varying load is by the use of compound-wound generators. As the load changes, the field strength is changed, owing to the current in the series-field coils, and the voltage either remains approximately constant or rises slightly with increasing load in order to compensate for increasing voltage drop in the conductors leading to the devices using electricity.

This method of regulation is satisfactory for operating motors or other devices not appreciably affected by moderate voltage changes. It is also satisfactory for some loads consisting wholly of lamps. But when lamps and motors are operated on the same circuits, the lights may be disagreeably affected by the

voltage changes unless other means of voltage regulation are employed.

73. The Tirrill voltage regulator automatically adjusts the field strength of a generator by short-circuiting the field rheostat when the voltage is low. Two sets of contacts are employed, each operated by electromagnets, as indicated in Fig. 53. The main control magnet coil is connected across the circuit with external resistance in series. When the voltage is low, this magnet is weakened, and the main contacts are held closed by a spring. The coils of the relay magnet are also connected across the circuit with external resistance in series, but they

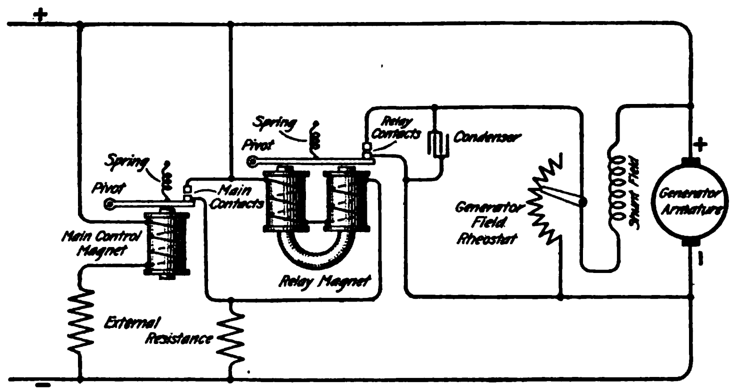


FIG. 53

are shunted by the main contacts. While the main contacts are closed, the coils of the relay magnet are thereby weakened, so that the relay contacts are held closed by a spring. The relay contacts are in a circuit shunting the field rheostat, and while these contacts are closed the rheostat is cut out of the shunt-field circuit, so that the generator voltage builds up rapidly. When the voltage becomes too high, the main contacts open, followed immediately by the opening of the relay contacts, thus placing the rheostat in the field circuit and reducing the voltage.

The resistance in the rheostat is high enough to affect the generator voltage quickly; usually this resistance is enough to reduce the voltage to about two-thirds of its full value if left

in circuit continuously. The contacts therefore vibrate rapidly—probably from 300 to 600 times a minute—thus keeping the voltage very nearly constant. A condenser bridges the relay contacts and prevents injurious sparking; the current

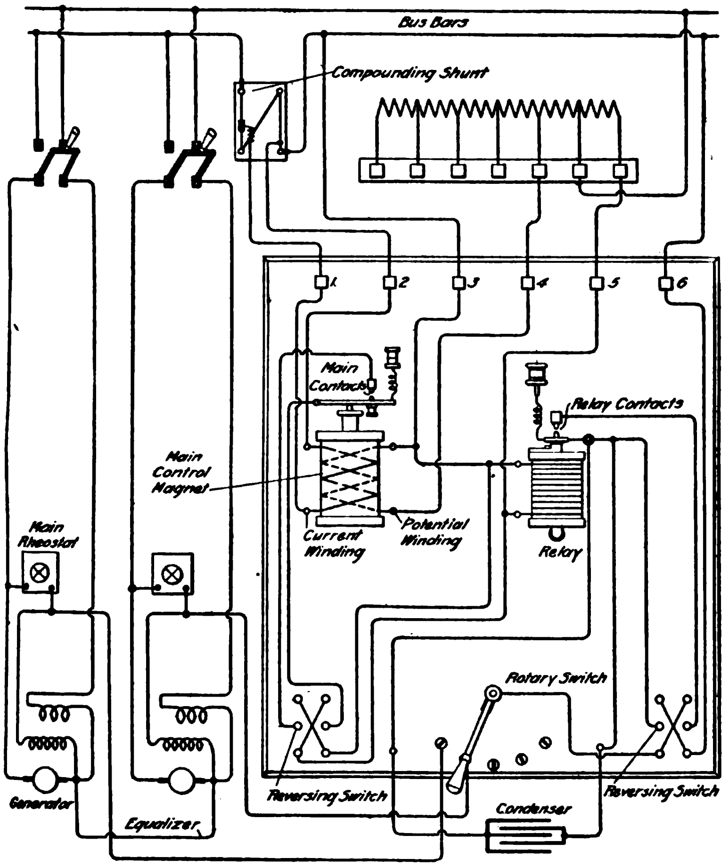
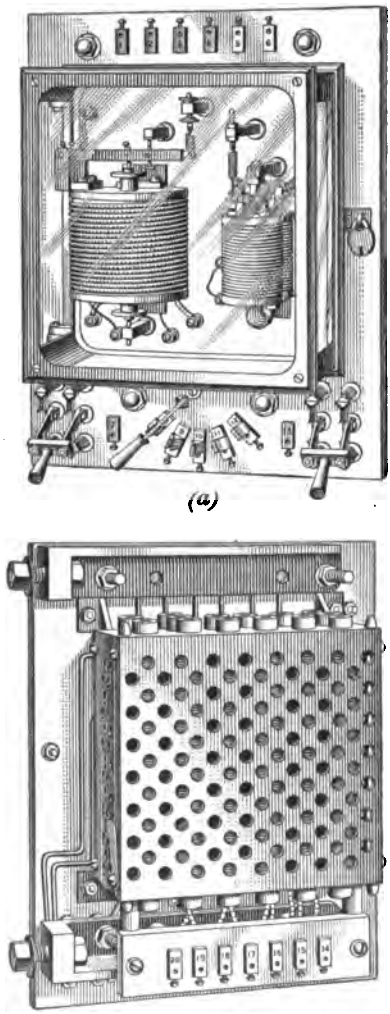


FIG. 54

through the main contacts is so small that such protection is unnecessary. When tested by means of an *oscillograph*, an instrument that records very small voltage changes, the generator voltage is found to vary only a fraction of a volt, and these variations have inappreciable effect on electric lights.

74. Fig. 54 shows a diagram of complete connections of a regulator for use with either shunt- or compound-wound generators of capacities up to 25 kilowatts, and Fig. 55 shows a front view (*a*) and a rear view (*b*) of the regulator mounted on a marble base. As shown in Fig. 54, the main control magnet has both a potential winding connected across the generator terminals and a current winding connected across an adjustable low resistance, known as a *compounding shunt*, in the main circuit. The current winding therefore carries a fixed portion of the load current, depending on the adjustment of the compounding shunt. The magnetizing effect of this current opposes the effect of the current in the potential winding, thus acting the same as additional tension in the spring, tending to hold the main contacts closed. In order to open the main contacts, the generator voltage must therefore rise higher when the generator is loaded than when running light, and the greater the load the higher must be the voltage in order to open these contacts.



(*a*)

(*b*)

FIG. 55

A resistance with several taps, represented at the top of Fig. 54, is mounted in a case on the back of the panel, Fig. 55 (*b*),

and one terminal of the potential winding is connected with the tap that gives the desired voltage. Further adjustment can be made by changing the tension of the spring holding the main contacts closed; a thumb nut is provided for this purpose. At each lower corner of the panel is a double-pole, double-throw switch, by means of which the direction of current through the contact points can be reversed periodically, thus prolonging the life of the contacts.

75. The voltages of several small compound-wound generators operating in parallel can be controlled by a regulator connected with one of the generators. This generator will then be most sensitive to sudden changes of load on the system, but the series fields and equalizers will soon cause the other generators to take their proper shares of the load. The regulator can be connected to any one of several generators by means of a rotary switch shown near the bottom of Figs. 54 and 55 (*a*). Shunt-wound generators do not operate successfully in parallel because of the difficulty of keeping the fields adjusted so as to divide the load properly.

76. Regulators for machines having capacities of more than 25 kilowatts sometimes have several relay magnets operated by one set of main contacts, each relay magnet controlling a section of the field rheostat. The burning action of the field discharge is thus distributed over several pairs of contacts so as to cause less injury. All the relay magnets operate simultaneously, and such a regulator is often used with several compound-wound generators by controlling each shunt field by one or more pairs of relay contacts. A regulator with ten relay magnets can control a total generator capacity of about 400 kilowatts either from a single machine or from several machines in parallel. For controlling the voltage of a larger generator, the generator is usually separately excited and the controller is used in connection with the exciting generator, raising or lowering its voltage in order to adjust the field of the main generator.

DIRECT-CURRENT MOTORS

CLASSIFICATION

SIZES OF MOTORS

1. Widely varying power requirements for industrial processes have led to the development of an endless variety of sizes, types, and classes of direct-current motors with widely varying characteristics. All manufacturers, however, list motors in general classes or types, some of which are comparatively limited in application and others very broad.

Direct-current motors may be classified according to size, field winding, speed, degree of enclosure, mechanical characteristics, service conditions, and the class of application for which they are intended.

2. According to size, motors are usually classified by manufacturers as *small* and *large*. No definite dividing line exists between the two, since what may be called a small motor by one manufacturer, may have an equivalent rating in another classification by another manufacturer. Large motors are seldom listed as such, except occasionally those of very large capacity. The use of small motors has become so common, however, that almost every motor manufacturer has a line of so-called small motors, often called *small power motors* to distinguish them from fan motors.

FIELD WINDING

3. According to field winding, all direct-current motors are in three classes, namely, *shunt*, *compound*, and *series*. Shunt-wound motors start and operate with current input proportional to the torque, or turning effort, and run at practically constant speed at all loads. The current input to a series motor varies less than directly proportional to the torque and the speed varies widely with varying load. For example, at twice full-load torque, a shunt motor requires approximately twice full-load current and operates at only a trifle below its full-load speed, while a series motor requires considerably less than twice full-load current, but operates at much below full-load speed. Compound-wound motors have characteristics intermediate between those of shunt and series motors, resembling most closely the one that its field winding most nearly resembles.

4. The **characteristics** of a motor are its variation of speed, torque, and efficiency with varying load. Fig. 1 shows characteristic curves of a 50-horsepower motor; the line amperes, corresponding to the load, are represented by the distance from the left-hand margin; the speed in revolutions per minute, the output in horsepower, the torque in pounds at 1-foot radius (pound-feet), and the efficiency in per cent. are represented by distance from the lower margin. In Fig. 1 (*a*), the efficiency, speed, horsepower, and torque of a compound-wound motor are represented by the full-line curves, and the speed and torque of a shunt-wound motor by the dotted-line curves; the efficiency and horsepower are approximately the same for both windings. The curves in (*b*) show characteristics of a motor of the same capacity with series-field windings.

5. The curves of compound and series motors, Fig. 1, show actual results obtained from standard motors of the same rating, but with the two types of winding; the speed and torque curves of the shunt motor are theoretical, but would be closely approximated in practice. The difference in speed

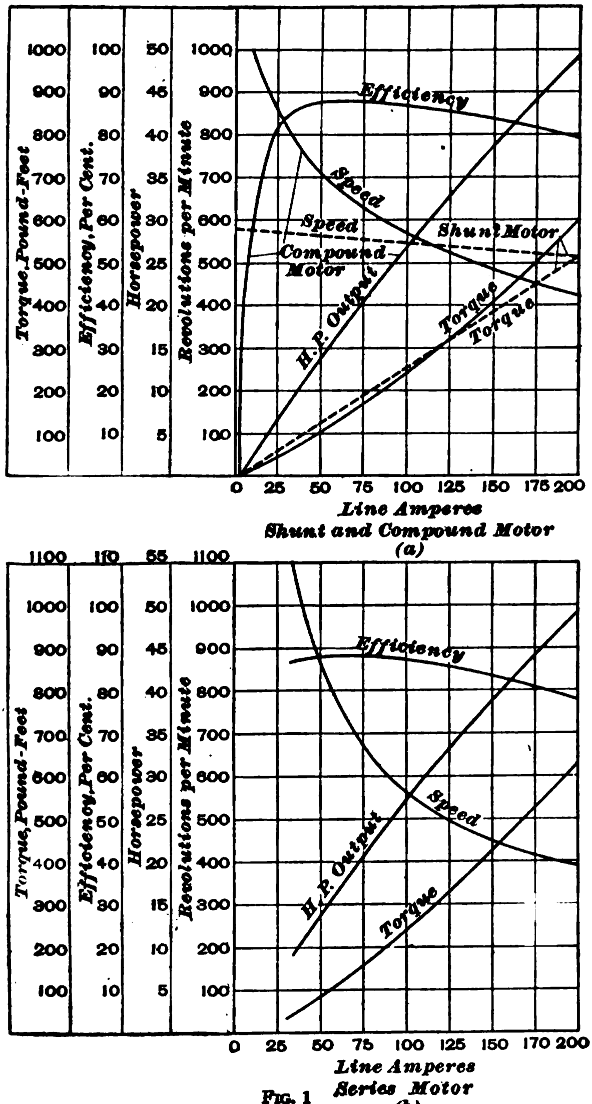

Torque, Pound-Feet
Efficiency, Per Cent.
Horsepower
Revolutions per Minute
Efficiency
Speed
Speed
Compound Motor
Shunt Motor
H. P. Output
Torque
Torque
0 25 50 75 100 125 150 175 200
Line Amperes
Shunt and Compound Motor
(a)
Efficiency
Speed
H. P. Output
Torque
0 25 50 75 100 125 150 170 200
Line Amperes
Series Motor
(b)

FIG. 1

variation is forcibly illustrated by readings from the curves, as recorded in Table I.

The speed curve of the series motor shows rapid increase of speed with decreasing load. At no load, the speed of such a motor would be too high for safety; this fact accounts for the blanks in the last column of the table. Series motors should never be used where there is a probability of operating at no

TABLE I

INFLUENCE OF FIELD WINDING ON MOTOR SPEED

Amperes	Speed, Revolutions per Minute		
	Shunt	Compound	Series
10	580	1,000	
25	578	850	
50	570	710	860
75	562	630	675
100	555	575	560
125	525	540	495

load or at very light load; for example, they should not be used in belted service, because the belt might run off, leaving no load on the motor and allowing it to race.

6. In addition to the foregoing winding classifications are **commutating-pole,** or **interpole, motors,** in which field poles with series windings are arranged between the main poles to assist in obtaining good commutation. Such motors are usually so designed that the series winding on the commutating poles has practically no effect on the speed. A few compensating series turns are frequently placed on the main poles of shunt motors of this class in order to keep the speed nearly constant at all loads when the motor is operated at high speed. Without such compensating turns and with resistance in the shunt-field circuit for high-speed operation, increased load is in some cases accompanied by increased speed on account of the overbalancing effect of armature reaction and of the

commutating poles. These compensating turns serve merely to render the motor operation stable when the shunt field is weakened for speed adjustment.

7. **Consequent-pole motors,** though rarely used, form another class. Alternate field poles have no windings, but are magnetized in consequence of the winding on the other poles.

SPEED

8. According to speed, both alternating-current motors and direct-current motors may be classified in the same way. Alternating current is fully explained in later Sections. The following speed classification applies to direct-current motors only, except where otherwise specified.

9. **Constant-speed motors** are those of which the speed at all loads between no load and full load does not vary more than a fixed per cent.—usually 20 per cent.—from full-load speed. Examples are synchronous and induction motors, both alternating current; shunt-wound motors; and compound-wound motors with comparatively light series-field winding.

10. **Multispeed motors** are those capable of operating at more than one constant speed. Examples are induction (alternating current) motors with field windings capable of more than one grouping and direct-current motors with two armature windings and two commutators.

11. **Adjustable-speed motors** are those capable of speed adjustment by regulation of shunt-field current. Shunt motors in this class operate as constant-speed motors at any field adjustment; compound-wound motors are also in this class as long as the speed does not vary more than 20 per cent. from full-load speed at any load or field adjustment.

12. **Varying-speed motors** are those of which the speed varies widely with the load, decreasing when the load increases and increasing when the load decreases, such as series motors and motors having only enough shunt-field winding to keep the

speed within safe limits at no load. Some alternating-current motors are also in this class.

13. In addition to the foregoing speed classification, motors are sometimes classified as *slow speed*, *medium speed*, and *high speed;* but these classes are not well defined and mean little except when used in connection with the motors of some particular manufacturer.

ENCLOSURE

14. According to the degree of enclosure, motors are *open type*, *semienclosed type*, *entirely enclosed type*, and *enclosed ventilated type*.

15. **Open-type motors** are so made as to obtain the greatest possible cooling effect from air circulation around the

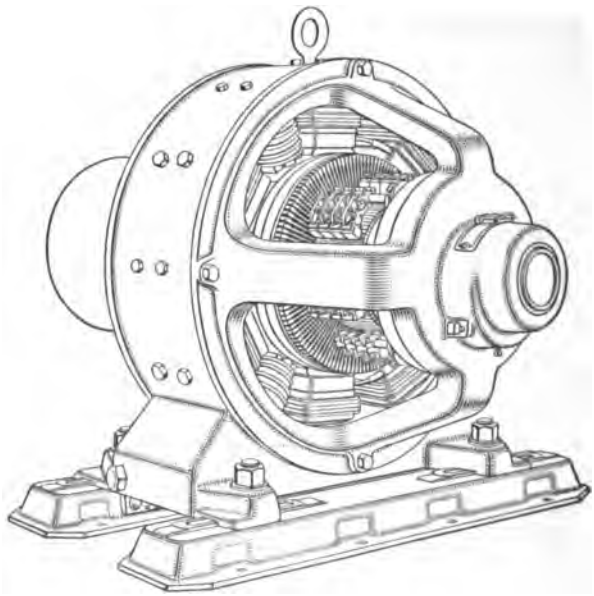


FIG. 2

parts subject to heating, by leaving those parts open to the passage of air. The skilful designer arranges the rotating element to set air in motion and aims to direct the air-currents around

and over the working parts—field coils, armature, and commutator. Of two equally rated motors, the one emitting a breeze of heated air while operating is better ventilated and generally more desirable than the motor around which the air remains stagnant. Figs. 2 and 3 show open-type direct-current motors.

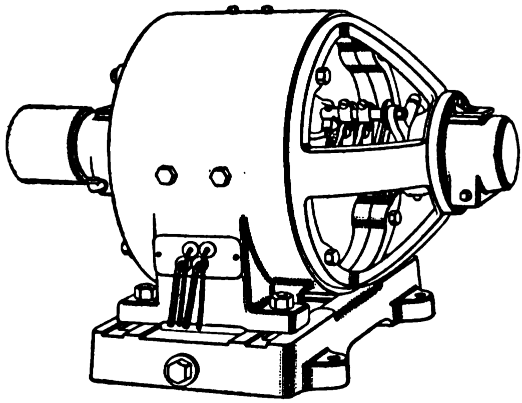


FIG. 3

16. Semienclosed motors differ from open motors only by the provision of covers over all openings to exclude coarse articles. Such covers restrict ventilation, but do not entirely stop it. They are sometimes cast in the form of grids with small openings, as in Fig. 4, sometimes formed of perforated sheet metal, as in Fig. 5, and sometimes made of fine wire gauze, according to the service conditions or the manufacturer's choice. The degree of enclosure depends on the materials to be excluded.

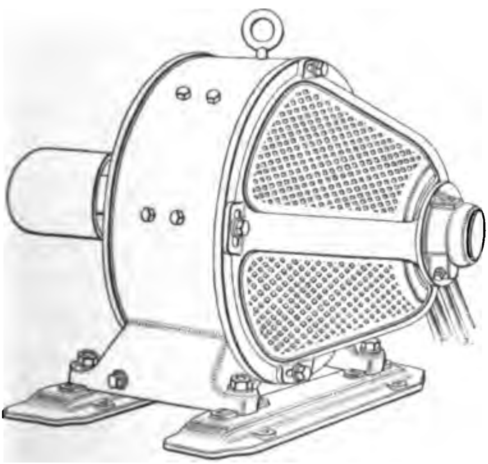


FIG. 4

17. Entirely enclosed motors have no uncovered openings through which foreign particles of any description might enter. All openings

are closed by tight-fitting covers, although the motor frames employed may be the same as those for open and semienclosed motors. Gaskets of rubber or some other suitable material may be provided under the covers to keep out dust and possibly to render the motors splash-proof. Such motors are sometimes said to be moisture-proof, but it is doubtful whether they can be made proof against the entrance of moisture if operated in damp places and allowed to stand idle long enough to cool off occasionally.

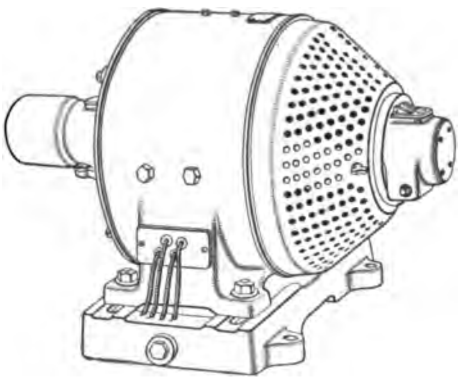


FIG. 5

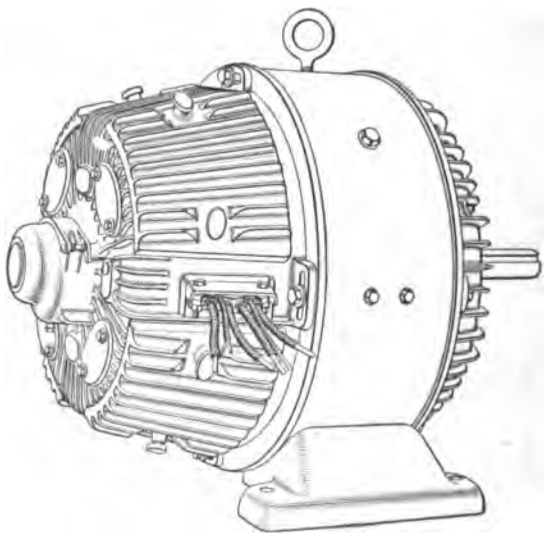


FIG. 6

18. Ordinary enclosed motors have no self-ventilating properties whatever, and the ratings are therefore considerably

less than those of open motors of corresponding size. Few open-type shunt or compound motors can be provided with enclosing covers and operated on their rated voltage, even if the motor rating is reduced. In most cases, the shunt-field coils would overheat under such conditions. Sometimes a standard motor can be fully enclosed by reducing its rating somewhat and using some resistance in series with the shunt field or reducing the operating voltage. Ordinarily, special windings are preferable.

Figs. 6 and 7 show types of entirely enclosed motors. The motor shown in Fig. 6 has an unusually small frame for its rating; both bearing brackets and all covers are ribbed in order to increase the radiating surface for heat dissipation. The motor frame shown in Fig. 7 is large enough in proportion to its output to make such construction unnecessary.

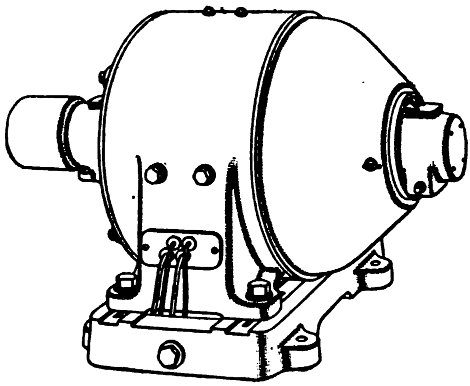


FIG. 7

19. In addition to the foregoing distinct classes, according to enclosure, any combination of these classes may be used. For example, part of a motor may be entirely closed and part semiclosed or open. In some cases, grid covers are provided for the top openings, while the lower openings are not covered.

20. Enclosed ventilated motors, Fig. 8, are protected from the entrance of dust, and are provided with ventilation permitting operation in most cases at full open rating. This ventilation results from a blower or a set of fan blades located inside the motor and driven by the armature. Air tubes connect the inside of the motor frame with some outside source. The blower causes air to circulate through the motor and carry away the heat. When several enclosed motors

are to operate in the same vicinity, a single independently driven blower with tubes leading to all the motors is sometimes used to good advantage.

MECHANICAL CHARACTERISTICS

21. Among the principal mechanical modifications of motors are *horizontal-shaft motors*, including those with back gears, and *vertical-shaft motors*. These are the general classes; minor modifications are two-bearing motors, three-bearing motors, motors with self-contained bearings (in the end brackets), motors with pedestal bearings, motors with idler pulleys for preventing belt slippage, etc.

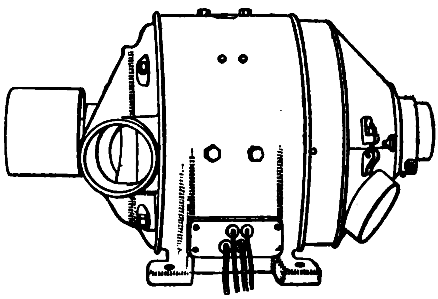


FIG. 8

22. Horizontal motors, Figs. 2 to 12, inclusive, may be arranged for driving by belt, chain, pinion, or coupling. They may or may not require a third bearing outside the pulley, pinion, or sprocket, depending on size, speed, and service conditions.

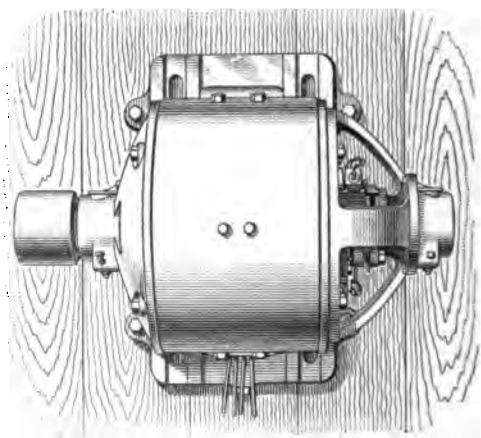


FIG. 9

If the shaft is kept horizontal, such motors can usually be mounted upright on a floor or a foundation, as indicated in preceding illustrations, sidewise on a wall or other vertical support, as in Fig. 9, or inverted on a ceiling, as

in Fig. 10, up to sizes too large for side-wall or ceiling mounting. When automatic oil-ring lubrication is employed, the bearings must be so arranged for each mounting that the oil reservoirs are directly under the journals. Motors such as those shown have bearings in brackets attached to the frame so as to be capable of turning 90° or 180°, to suit different mountings.

23. Back-geared motors, Figs. 11 and 12, are applicable in some cases where slow driving speed with comparatively high motor speed is desirable. Such motors have two horizontal shafts, one of which carries the armature and rotates in main bearings *a*, and the countershaft, or back shaft, *b*, which rotates

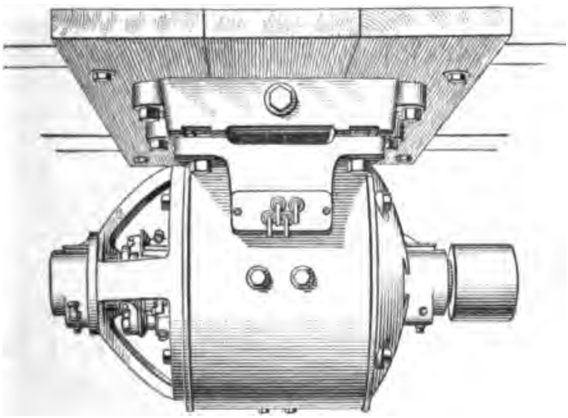


FIG. 10

in bearings bracketed to the motor frame so as to maintain fixed distance between the two shafts. The teeth of a pinion on the armature shaft mesh with those of a gear-wheel, or gear, *c* on the countershaft, and as the gear is much larger than the pinion, it rotates at proportionately slower speed.

Let s = speed of pinion, in revolutions per minute;
d = diameter of pinion, in inches;
n = number of teeth of pinion;
S = speed of gear, in revolutions per minute;
D = diameter of gear, in inches;
N = number of teeth of gear.

Then, $$\frac{S}{s}=\frac{d}{D}=\frac{n}{N} \qquad (1)$$

and $$S=\frac{s\,d}{D} \text{ or } \frac{s\,n}{N} \qquad (2)$$

For example, if the diameter of a pinion is 4 inches and the diameter of its gear 24 inches, the gear speed for a pinion speed of 1,700 revolutions per minute is

$$S=\frac{1{,}700\times 4}{24}=283\tfrac{1}{3} \text{ R. P. M.}$$

24. Back-geared motors are usually provided with a countershaft having the free end fitted to receive a pinion or a pulley for connection to the driven machine. The pinion and the wheel may be unguarded, as in Fig. 11, or they may be

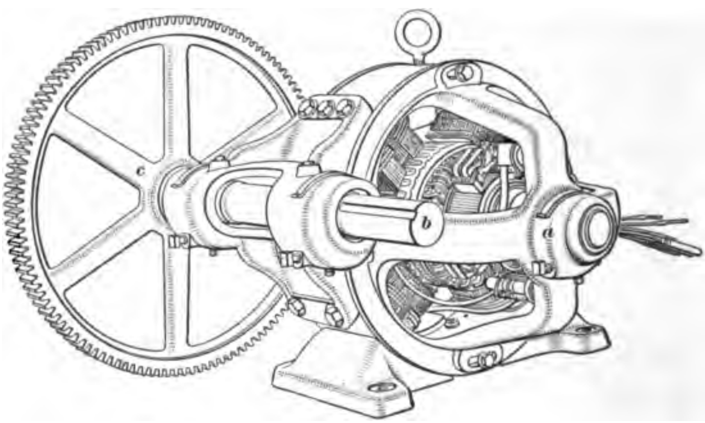


Fig. 11

covered with shields, as in Fig. 12. Unguarded gears are dangerous if they are located where attendants may come near them or where any foreign substances may be caught by them.

25. Vertical-shaft motors are supplied each with one thrust bearing to carry the armature and at least two guide bearings. The thrust bearing may be placed at either end of the shaft, but it is generally located at the upper end, the

armature being suspended. This bearing generally consists of hardened-steel balls rolling between steel rings in an oil bath. A cap, or ring, fastened to the upper end of the motor shaft serves to suspend the armature on the thrust bearing. The thrust bearing is usually designed to support some weight additional to that of the armature; as, for example, the blades of a fan, or blower, or the impeller of a rotary pump.

26. The purpose of the guide bearings is to keep the armature shaft in proper alinement; they are lined with some anti-

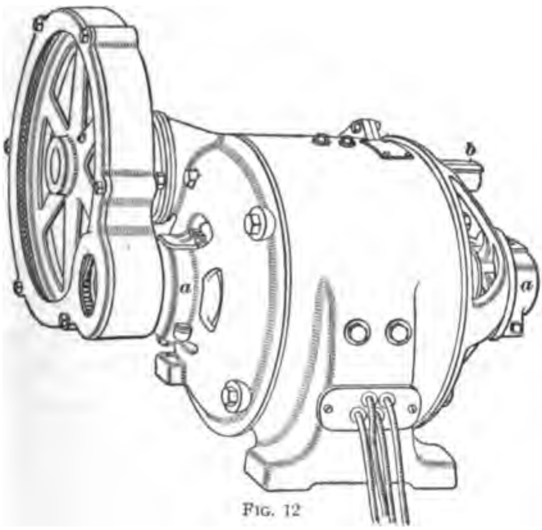


FIG. 12

friction metal and are lubricated by means of oil or grease cups that feed the bearing surfaces through suitable channels or by oil reservoirs from which the oil is fed automatically to the bearing surfaces. Automatic lubrication is the later method and has proved to be very successful; bearings of this type in vertical motors require attention no more frequently than do the ordinary ring bearings of horizontal motors.

27. Fig. 13 shows a vertical motor having automatic lubrication. At the bottom of each guide bearing is an oil reservoir, which is filled through a horizontal pipe having an oil gauge *a* at the outer end. When the shaft rotates, oil works

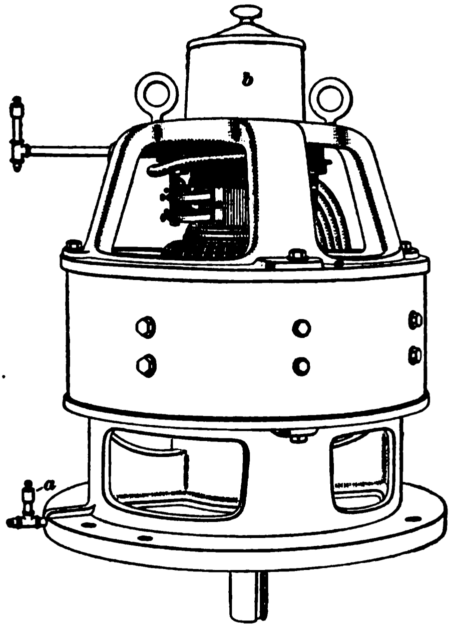


Fig. 13

upwards through spiral grooves in the bearing linings and over the bearing surfaces. Surplus oil flows back into the reservoir. The ball-thrust bearing is inside the cylindrical case *b* at the top of the motor, and the balls are below the surface of the oil in the upper reservoir, thus being effectively lubricated.

28. Vertical motors usually drive from the lower end through direct coupling. They can, however, be arranged for belt drive, but the side pull of the belt may necessitate specially heavy construction of shaft and guide bearings or possibly a third bearing below the pulley.

SERVICE CONDITIONS

29. According to the service for which they are recommended, motors are generally rated for *continuous service, intermittent service*, and *periodic service*. Motor manufacturers generally look closely into the conditions of the service to be performed and endeavor to aid in the selection of motors suited to the service.

30. Continuous-service motors are ordinarily guaranteed to carry full-rated load continuously for any desired period with temperature rises not exceeding the guaranteed limits. As ordinarily rated, such motors are capable of carrying some overload temporarily without injurious sparking or

heating. Continuous service in connection with a motor rating implies constant torque, such as is required for driving fans, blowers, pumps, line shafts, and endless-belt grain elevators. The fact that a motor runs continuously does not always necessitate a continuous-service rating; this rating is necessary only when the load is continuous or nearly so.

31. Intermittent-service motors are generally guaranteed to carry full-rated load continuously for a limited period within specified heating limits. The duration of the guaranteed period depends on service conditions, and the motor windings can be insulated for either high- or low-temperature limits. For example, motors are built for service periods of a few minutes up to continuous service, and for guaranteed temperature rises of approximately 40° C. up to 75° or 100° C. Overload guaranties are not usually given on intermittent-service motors other than momentary overloads. Examples of intermittent service are the operation of some machine tools, passenger and freight elevators, electric vehicles, hoists, cranes, etc. Motors with intermittent-service ratings may be employed where operation is continuous, provided the torque is intermittent, as on many machine tools.

32. Periodic service for motors is also intermittent, but consists of a regular and continuously recurring cycle of operations. A typical cycle for such a motor is that required to operate a shovel for excavating; filling the shovel, hoisting, swinging into position for dumping, and returning for refilling necessitates work at different rates and in both directions of rotation, the same cycle being repeated indefinitely with little variation. Service of this nature is found in several industries.

APPLICATION

33. According to application, motors are classed as *mill motors*, *crane-and-hoist motors*, *elevator motors*, *vehicle motors*, *railway motors*, *mine motors*, etc. Each type named is designed with electrical and mechanical characteristics suited for the application. For example, motors for heavy service, such as

in steel and iron mills, in railway work, and on cranes and hoists, are distinguished by very heavy and substantial construction capable of withstanding heavy shocks and great stresses. An example of how motors are modified to suit an application is shown in Fig. 14; this motor is built as a component part of the portable drill.

DIRECT-CURRENT MOTOR CONTROL

TORQUE

34. The **torque,** or *turning effort,* developed by any direct-current motor depends on the current in its armature conductors and on its field strength. The voltage effective in causing current in the armature conductors is the difference

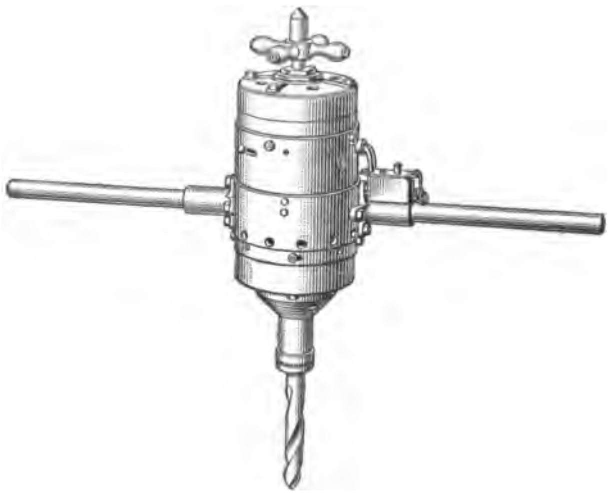


FIG. 14

between the voltage e applied to the brushes and the counter voltage e' generated in the armature. The current I in the armature conductors is, according to Ohm's law, the quotient of this effective voltage divided by the armature resistance r measured between positive and negative brushes, or

$$I = \frac{e - e'}{r}$$

35. The counter voltage e' is caused by the motion of the armature conductors in the magnetic field, that is, by the generator action of the armature; the counter voltage is therefore proportional to the speed of the armature and to the strength of the field. The resistance r remains constant, except for small changes caused by temperature variations. At any field strength, the speed automatically adjusts itself until the current is sufficient for the required torque. For example, assuming that e and the field strength remain constant, increasing the load so as to require more torque causes the speed to decrease until $e-e'$ is large enough to cause the necessary increased current. On the other hand, assuming that e and the torque remains constant, decreasing the field strength causes the motor speed to increase so as to keep $e-e'$ at the proper value.

A trolley car in ascending a grade always slows down because additional torque is required of the motors. This additional torque necessitates more current, and, consequently, less counter voltage, and as such motors are series-wound the increased current strengthens the field and causes still further speed reduction, as is explained in the early part of this Section.

MOTOR STARTING

36. When at rest, the counter voltage of a motor is zero and the formula of Art. 34 becomes $I=\frac{e}{r}$. Since in all except very small motors the armature resistance r is very small, the voltage e at the brushes must be low in starting in order that the current I may be kept within safe limits. Switching full-line voltage E on to a motor to start it would in most cases result in current in the armature conductors so large as to overheat them and ruin their insulation.

The applied voltage must therefore be reduced when starting a motor. For general purposes, the only practicable way of obtaining this reduction is by passing the armature current through a resistance R external to the armature. Since

the voltage drop in this resistance is the product $I R$, the voltage applied to the armature is $e = E - I R$.

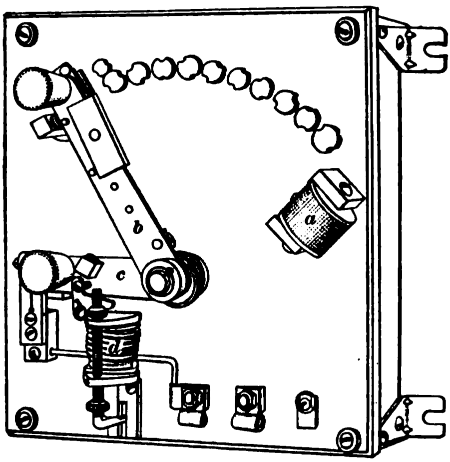


Fig. 15

37. As the counter voltage e' builds up, the impressed voltage can be increased by reducing the resistance R. In practice, this reduction is effected in steps until R is all out of circuit. The number of steps depends on the size of the motor, more steps being required for a large motor than for a small one. More than ten or twelve steps is rarely necessary.

38. **A motor starter** is essentially a resistor with a switching device to remove the resistance in steps from the armature circuit as the speed increases. The starter may be self-contained in the form shown in Figs. 15 and 16, sometimes called *starting rheostat*, or *starting box;* it may also consist of the same essential parts with the resistor and switching device mounted separate from each other.

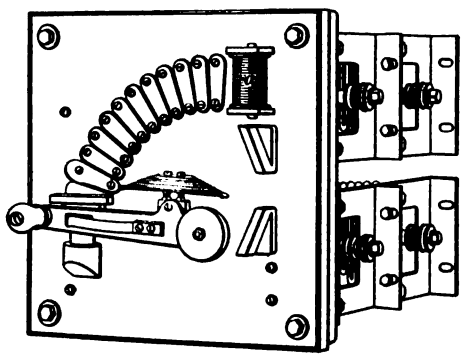


Fig. 16

Fig. 17 shows a *universal starting panel*, so called because the motor starter is mounted on a panel beneath a circuit-breaker, which opens automatically if the motor current becomes too great. The circuit-breaker can also be *tripped*,

or opened, by hand, thus serving both for overload protection and as a line switch. Panels of this type are also made with a line switch and line fuses instead of the circuit-breaker.

39. The most important part of a motor starter is the switching device, which may be of the **face-plate type** with contacts arranged as shown in Figs. 15, 16, and 17, or with contacts in the form of series of hand-operated switches, known as the **multiple-switch type,** Fig. 18. The switching device may also be of the **automatic switch, or contactor, type,** Fig. 19. In this case, the switches close automatically, each cutting out a section of resistance when the motor speed has accelerated to the proper point.

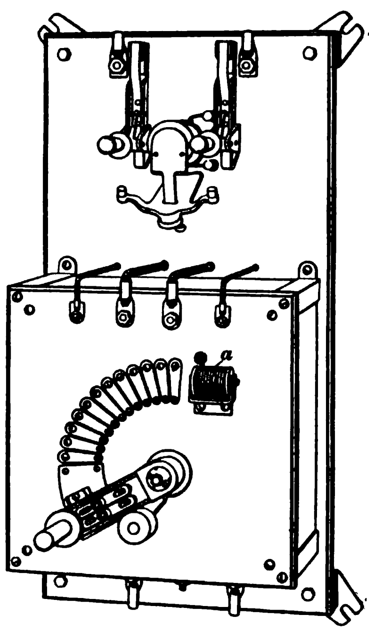


FIG. 17

40. Protective Devices. Nearly all direct-current motor starters are so arranged that in case the line voltage fails the motor is automatically disconnected from the line, and the switching mechanism returns to a position such that the motor must be again started in the usual way after the voltage returns. The return of voltage after temporary failure cannot then injure the motor by the sudden application of full voltage. This automatic **no-voltage** or, more correctly, **low-voltage, release mechanism** consists of a magnetic latch that holds the switching device closed until the voltage falls too low, when the latch releases and a return spring throws the handle or the switches to the off-position. These magnetic release coils can be seen at *a* on the starters shown in Figs. 15, 16, 17, and 18; the starter shown in

Fig. 19 is operated by magnets depending for excitation on the voltage, and failure of voltage allows the switches to open.

41. Many starters also include protective features to preserve the contacts from injury. Among these are **arc shields** of refractory material, as at *a*, Fig. 19, to prevent the formation of destructive arcs when the circuit is opened; also **magnetic blow-out coils** that create a strong magnetic flux across the path of the arc, blowing it sidewise until disrupted. In this case the arc is a conductor, and any conductor carrying current

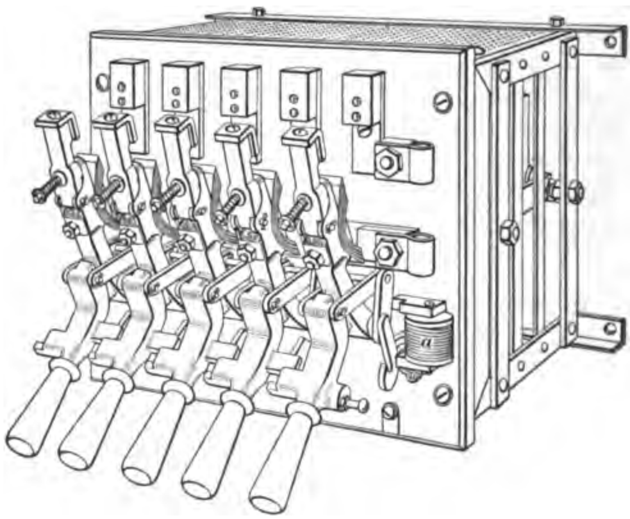


FIG. 18

in a magnetic field is forced sidewise by the reaction of the current and the flux.

42. Overload protection is also incorporated with starting devices by arranging a magnetic latch to release the switching device if the current in the armature becomes too great for safety. A release of this sort that operates by demagnetizing the low-voltage release magnet is not effective against overloads while starting a motor, since it affords protection only when the switching device is in the running position. The starter shown in Fig. 15 has an overload release that is

effective whenever the starting lever *b* is over any of the resistor contacts.

The connections are shown in Fig. 20, in which the reference letters are the same as those in Fig. 15. The low-voltage release coil *a* is energized when the starting lever *b* rests over any of the resistor contacts *1*, *2*, *3*, etc., provided the overload release lever *c* remains in the position shown in both illustrations. If the current becomes too great for safety, the overload coil *d* releases lever *c*, which is thrown open toward lever *b* by a spring, thus opening the motor circuit. Both levers must then be

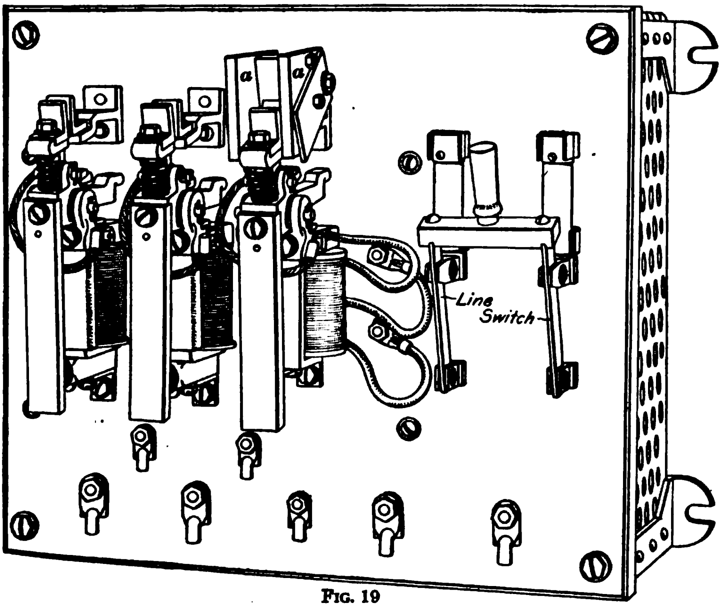


FIG. 19

returned to the off-position at the extreme left before another start can be made. The field connections shown by full lines are those of a shunt motor; the series field of a compound-wound motor is connected as shown by the broken lines, the direct circuit between the series-field terminals *e* and *f* then being open.

43. Panels with both low-voltage release devices and circuit-breakers, as shown in Fig. 17, or with fuses afford full

protection against injury by voltage failures and overloads. The choice between fuses and circuit-breakers depends on the service conditions. Fuses are better where overloads are rare or of such brief duration as to work no injury; circuit-breakers are preferable where injurious overloads may occur frequently and the continued replacement of fuses would be troublesome.

44. Starting and Stopping a Motor.—Starting a motor with a starter like that shown in Figs. 15, 16, or 17 is accomplished by first closing the line switch and then moving the starting lever over the row of resistance contacts, frequently called *steps* and *points*. The movement should be slow enough to allow the motor speed to accelerate smoothly. On the point at the extreme right, the lever is held by the low-voltage retaining magnet; this is the point on which the lever remains while the motor is running and is therefore called the ***running point***.

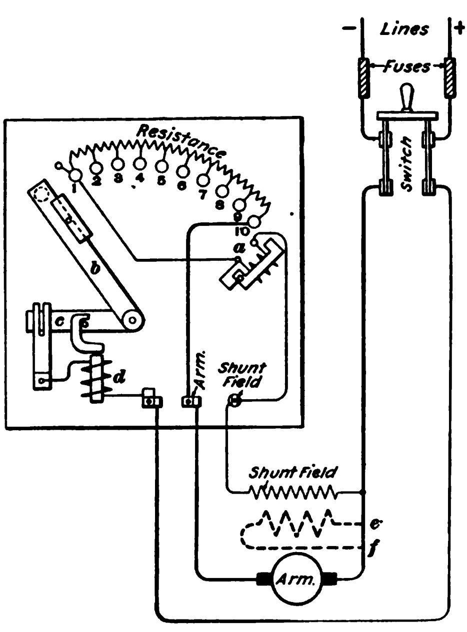


Fig. 20

The lever will not remain at rest on any intermediate point and must not be held there longer than necessary for the speed to pick up.

Starting with a multiple-switch starter, such as is shown in Fig. 18, is accomplished by closing the switches successively, beginning with the one nearest the release coil *a*. They should not be closed more rapidly than the motor speed can accelerate, nor more slowly than is necessary for smooth acceleration.

An automatic starter, such as is shown in Fig. 19, needs no further attention after closing the line switch; the magnetic contactors close successively as the speed accelerates.

45. Stopping a motor with any of the starters illustrated is generally best accomplished by opening the line switch or circuit-breaker. Such a circuit-opening device should be a part of every motor installation, as indicated in Fig. 20. On opening this switch the motor speed will decrease until the magnets release the switching devices, which will automatically return to position for the succeeding start.

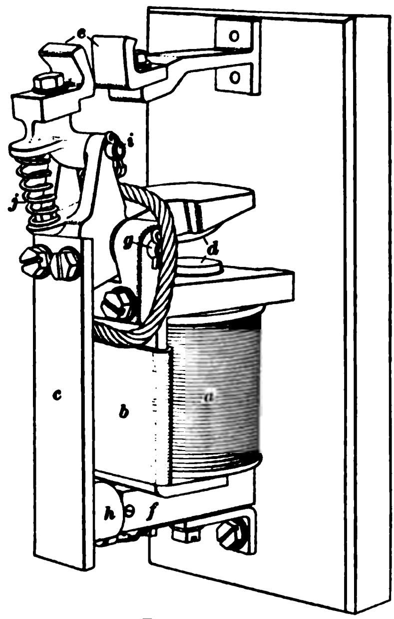


FIG. 21

46. Automatic Starting Switches.—The operation of the automatic starter shown in Fig. 19 may be explained by reference to Fig. 21, which illustrates one of the switch units, or contactors. These contactors are made especially for starters, and are variously called *series switches*, *series contactors*, and *magnetic lock-out switches*, the last name referring to the method by which their operation is delayed. The magnet coil *a* is series-wound, that is, it carries the armature current, and the switch is so made that it cannot close while the current through this coil exceeds the predetermined value for which adjustments are made.

Two return paths are provided for the magnetic flux outside the magnet core, one through a *magnetic shunt* *b* and the other through a vertical iron strip *c* attached to the moving element. The magnetic pull across the air gap *d* tends to close the contacts *e*, while the magnetic pull between the lower end of the

iron strip *c* and the pole *f* tends to hold the contacts open. A copper band around the magnetic shunt *b* prevents sudden changes of flux, and the cross-section of this shunt is so small that it becomes highly saturated when the magnetizing force is high.

When the current in the coil exceeds the adjustment, enough flux passes through the iron strip *c* to hold its lower end against the pole *f*. But when the current decreases, the flux through the strip *c* becomes less until the pull across gap *d* becomes superior, and the moving element turns on its pivot *g*, closing the contacts *e* and causing the lower end of the strip *c* to swing outwards.

47. A self-locking nurled nut *h* serves to adjust the length of the gap *d* and thus adjusts the current at which the switch closes. The contacts *e*, in closing, touch first near the tips and then rock back toward the heels by turning the arm to which the moving contact is attached around the pivot *i*. In thus turning, the spring *j* is compressed, so that when the contacts open, the rocking motion is reversed and the circuit is opened at the tips of the contacts.

48. Several designs of series contactors, or switches, in addition to the one described are on the market. When several of these contactors are properly grouped in a starter and adjusted, they will close automatically, as soon as the line switch is closed, in the sequence and time necessary to bring the motor up to speed. In this case, the delay in operation of each switch is entirely owing to the current in the circuit.

49. Fig. 22 shows a **shunt contactor, or shunt-magnet switch,** the word *shunt* indicating that the magnet coil is connected across the circuit. The main contacts *a*, shown between the arc shields, are of the rocking type, as explained in Art. **47.** Shunt contactors do not operate on the magnetic lock-out principle previously explained, but interlocking contacts *b* are added when necessary to control the circuit of the coil operating the next switch in a group that forms a starter or controller.

The control current of shunt switches is only enough to excite the magnets and is so small that an ordinary snap switch or push-button switch can be used for controlling it, and can be located at any convenient point near or remote from the starter. For example, such a starter can be located near its motor and controlled by means of a small hand-operated switch some distance away. Closing the switch causes the contactors to close and start the motor; opening the switch causes the contactors to open and stop the motor.

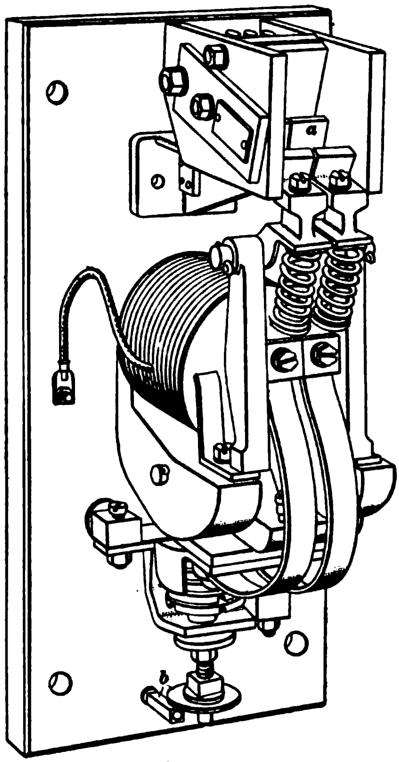


FIG. 22

50. With motors driving pumps and compressors, the control switch can be arranged so as to be operated by the movement of a float or a pressure gauge. The entire operation of the starter and motor can thus be made automatic, starting, for example, when the liquid in a tank reaches a predetermined level and stopping at another level. By this plan, the level of water in a tank or a reservoir or the pressure of air or gas in a receptacle can be maintained automatically within fixed limits without the continual presence of an attendant.

51. Connections of Automatic Starter.—Fig. 23 shows the connections of an automatic starter with one shunt contactor *1* and two series contactors *2* and *3*. The shunt contactor can be controlled manually or automatically from a distant point by means of the control switch, and the closing of

the shunt contactor is followed by the closing of the series contactors, each being delayed until the motor current falls to a safe value, as previously explained.

Closing the control switch places the coil *a* of the shunt contactor directly across the circuit, causing contactor *1* to close. The shunt field is thus fully excited and the armature circuit is closed through the starting resistance and series coil *b*. The

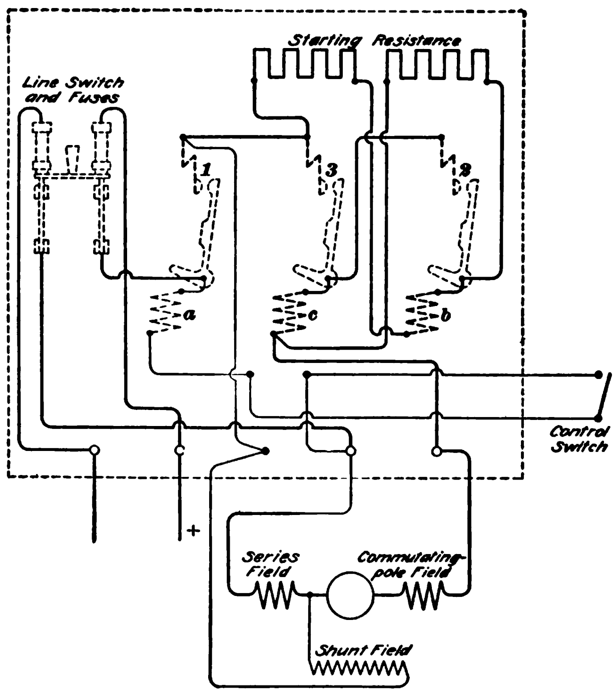


FIG. 23

motor starts, and as soon as the motor current falls to a safe value contactor *2* closes, short-circuiting one section of starting resistance and placing coil *c* in circuit. The motor speed continues to accelerate until contactor *3* closes, short-circuiting the remaining section of starting resistance and bringing the motor to full speed.

The delay in the operation of contactors *2* and *3* thus depends entirely on the motor current. A motor starting with a light

load is accelerated more rapidly than a motor starting with a heavy load.

52. The **starting resistor** for use with any device intended only for starting a motor is selected to carry the starting current during only the short period required to accelerate the motor speed. In most cases, these resistors would be overheated and possibly ruined if left in circuit long; that is, if too much time is taken to start. The time required to start a motor depends on its size and on the torque required at the start and during acceleration. A large motor usually requires more time than a small motor. Ten seconds is enough for fairly small motors starting with low torque; ½ minute is enough for most motors; while a few large motors under favorable starting conditions may require from 1 to 1½ minutes. In starting any motor with a manually operated starter, the successive steps of resistance should be cut out promptly as the motor speed accelerates.

MOTOR-SPEED REGULATION

53. Changes in the speed of a direct-current motor can be effected by changing the impressed voltage at the motor brushes or by changing the field strength of the motor. In either case, the motor speed automatically changes enough to keep the difference between the impressed volts and the counter volts at the value necessary for the torque. Regulation by varying the impressed volts may be called *armature control*, and regulation by varying the field strength *field control*.

54. Armature Control.—External resistance in series with the armature circuit serves to reduce the voltage at the brushes according to the formula of Art. **36**, namely, $e = E - IR$. If it is assumed that the field remains constant at full normal strength, the speed varies with the impressed volts e. Since the brush volts e cannot exceed the line volts E, all speed regulation by armature control is downwards from the full rated speed. The maximum speed occurs when e is nearest E; that is, when $IR = 0$, or when no resistance is in the external

circuit. The speed of any direct-current motor, whatever its class, can be regulated by armature control.

55. If the current in a direct-current armature remains constant while the resistance in the armature circuit is increased, the speed decreases; or, if the resistance remains constant while the current is increased, the speed decreases. With resistance in the armature circuit, therefore, the motor speed will not remain constant if the load conditions vary. For example, if the motor is operating a machine tool, every time the cutting tool comes to a hard spot or a deeper cut in the metal the motor will slow down very much more if its armature circuit includes regulating resistance than it would otherwise; when the tool has passed the hard spot or comes to a lighter cut, the speed increases again.

56. Since speed reduction by armature control is proportional to the voltage drop in the regulating resistance, it is accompanied by a corresponding loss of efficiency; for example, at 25-per-cent. speed reduction, 25 per cent. of the energy taken from the line is dissipated as heat in the resistance. This method of speed regulation is therefore inefficient, especially where full-load torque is required at reduced speeds.

57. Speed regulation by armature control is suitable for applications where the torque required to drive the load decreases rapidly as the speed is reduced and is constant at each speed; for example, the operation of fans, blowers, and some classes of pumps, which require very much less torque at low speeds than at high speeds. This method is also suitable where operation at reduced speeds is intermittent or brief, as on cranes and hoists. It is not recommended for cases in which the speed should remain practically constant at each adjustment while the torque may vary, as in operating many machine tools.

58. Field Control.—The counter voltage generated by a motor armature depends on the speed and on the strength of the magnetic field. The winding on a motor armature being fixed, the speed must change with each change of field strength

in order to maintain the relation $I = \frac{e-e'}{r}$ (Art. **34**). The normal rated speed of the motor being with full field strength, and any decrease of field strength being accompanied by an increase of speed, all speed regulation by field control is above the normal rated speed. The speed at any adjustment remains practically constant with all changes of load. The principal application of this method of control is to motors driving machine tools, for which field control is generally the ideal method.

59. The field strength of a motor can be weakened by reducing the excitation or by increasing the reluctance of the magnetic circuit. The former method is most commonly employed, the shunt-field current being reduced by inserting resistance in the field circuit. Since this resistance carries only the shunt-field current, which is comparatively small, the losses in the resistance are small.

60. Speed adjustment by field control is therefore usually confined to shunt motors, though the speed of some compound motors can be adjusted within comparatively narrow limits by regulating the shunt-field current. In general, caution should be used in operating a compound motor with a weakened shunt field, because the effect of the series field causes wide variations of speed with varying load; dangerously high speed would result if the load were removed from a compound motor when operating with a very weak shunt field. Not all shunt motors will commutate well when the field is weakened; and, therefore, only those of suitable design are susceptible of speed adjustment by this method.

61. Speed adjustment by changing the reluctance of the magnetic circuit is successfully employed, two methods being in use. In one, the central part of each field pole is arranged to be withdrawn an adjustable distance; a system of screws operated by a hand wheel enables the operator to withdraw these cores and thus weaken the field flux until the desired increased speed is obtained. By the other method, the armature is

withdrawn endwise from the field by means of a screw adjustment until the speed has increased to the desired point; the armature and pole faces are slightly cone-shaped, so that the air gap increases more rapidly than in proportion to the movement of the armature; that is, a 10-per-cent. movement of the armature means more than a 10-per-cent. increase of the air gap. Thus, wide speed adjustment is obtained with small movement.

SPEED-REGULATING DEVICES

62. Speed-regulating devices are the same in appearance and in general design as motor-starting devices, the chief difference being that the contacts and resistors of regulating devices are generally larger, better to withstand the more severe service imposed on them.

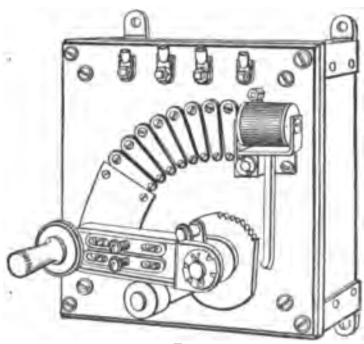


FIG. 24

63. Face-plate regulators of the box type, as shown in Fig. 24, are for adjusting resistances in the armature circuits for continuous operation. The moving contact can be left on any point, from which it can be readily moved to any other point by the operator and from which it is automatically released on failure of voltage; in case of such release, the handle returns promptly to the off-position. With such a regulator, the motor operates with varying speed on any point except full speed; that is, the speed increases when the load decreases.

64. Regulators of the type shown in Fig. 24 are much used with motors operating fans and blowers and in some cases with printing-press motors; such regulators are rarely used with machine-tool motors. The resistor must be designed for the service in each case, more resistance of lower carrying capacity

being necessary for fans and blowers than for most other classes of service. The current taken by a motor driving a fan or a blower varies nearly in direct proportion to the third power of the speed; hence, at reduced speed, the current is small and the resistance must be high to give the necessary voltage drop. Regulators for fan-and-blower service and for printing-press service have been standardized by most manufacturers.

65. A speed regulator of the universal type, Fig. 25, is similar in principle to that just described, but with a line switch and fuses, an overload release coil *a*, and four points *b* for field control. The operating lever is moved over the stationary contacts from left to right, as before, and can be moved on to the field contact points if speeds above normal rated speed of the motor are desired. The arm can be left on any point and will be automatically released in case of voltage failure, when it returns to the off-position. The rated motor speed is obtained when the arm is over the armature contact *c* and higher than rated speed is obtained when the arm is over any of the field contacts *b*. This type of controller is also standard for fans, blowers, and printing-press service.

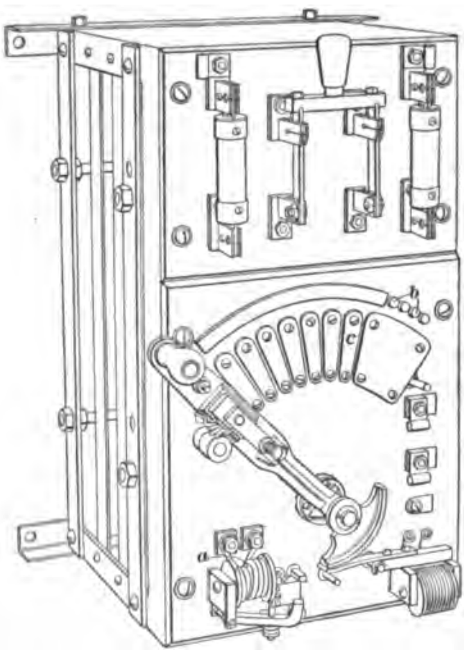


Fig. 25

66. Face-Plate Field Controller.—Fig. 26 shows a face-plate starting and controlling device for speed regulation

entirely by field control. The operating lever is double, one part carrying the moving armature contact and the other the moving field contact. In starting, both levers are moved to the right by means of one handle. At the extreme right, or full-speed position, the armature contact lever *a* is held by the retaining magnet, and the field contact lever *b* is moved back until the desired increased speed is obtained. The field-contact lever will remain on any point, but on failure of voltage the other lever is released and both move back to the off-position.

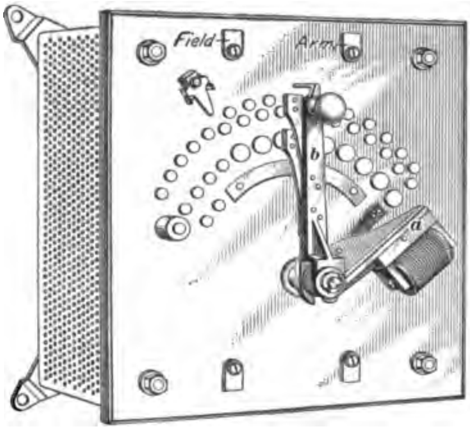


FIG. 26

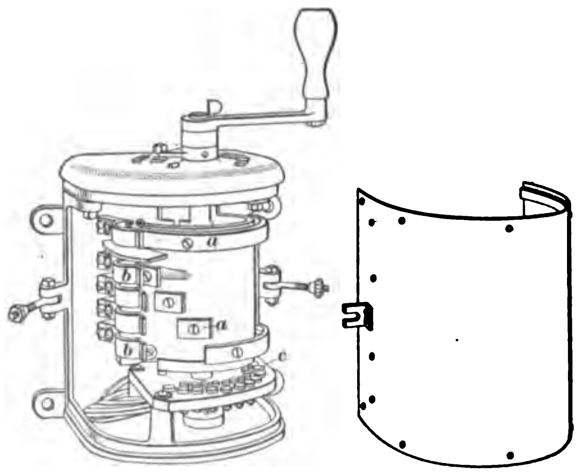


FIG. 27

67. The device just described is used principally with machine-tool motors, but is applicable to any motor where

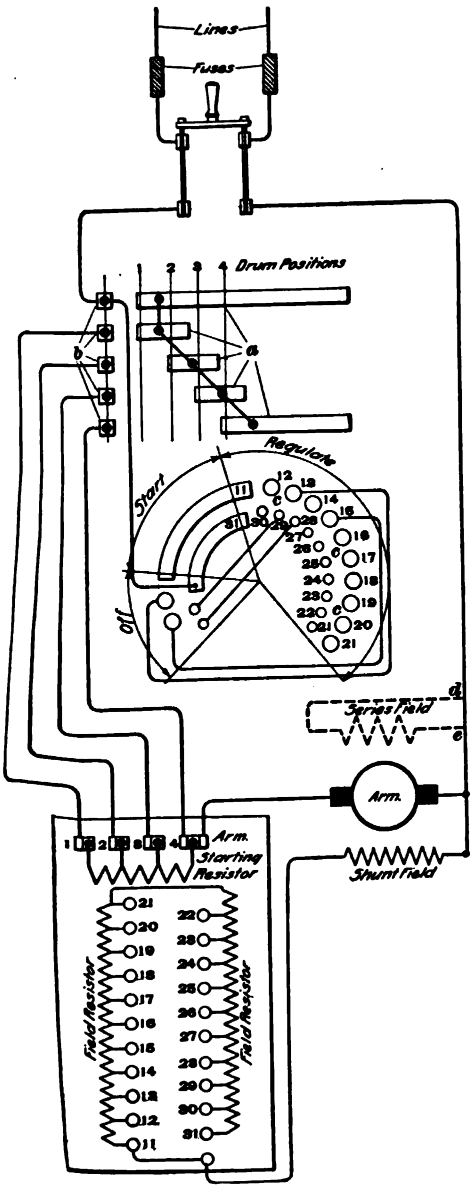


FIG. 28

wide speed adjustment above rated speed is desired. Provision can be made for both armature control and field control in regulators of this type.

68. Machine-Tool Controller. Fig. 27 shows a drum-type controller with the cover removed. This controller is designed for starting machine-tool motors and adjusting their speed by field regulation. Copper segments *a* attached to a drum slide under stationary fingers *b* when the drum is turned, and a contact arm also slides over the buttons *c*. The drum segments change the connections of the armature, and the contact arm changes those of the field coils.

69. A connection diagram of this drum-type controller is shown in Fig. 28. The drum segments

are indicated at *a*, the stationary fingers at *b*, and the field-contact buttons at *c*. The line switch and the starting resistor are connected with the fingers, and the field resistor with the buttons; no circuits are connected with the segments until they slide under the fingers. The central part of the figure shows the circular arrangement of the field contacts, while the lower part is a development showing how the steps of resistance are cut into or out of circuit. The similarity of numbers indicate the connections, which are not represented by lines in the diagram.

As the drum is turned, the drum segments *a* slide successively under the fingers *b* to positions *1*, *2*, *3*, and *4*, while the field-contact brush short-circuits segments *11* and *31*, giving full shunt-field strength. In position *1*, all the starting resistor is in circuit; in position *2*, one step is cut out; in position *3*, two steps are cut out; and in position *4*, all the starting resistor is out of circuit. At this point the motor runs with full shunt-field strength, but further rotation of the drum cuts the field resistor into circuit step by step, weakening the shunt field and increasing the speed to the desired point. The connections of the series field of a compound motor are shown by dotted lines; when a series field is used, the main circuit between terminals *d* and *e* is open.

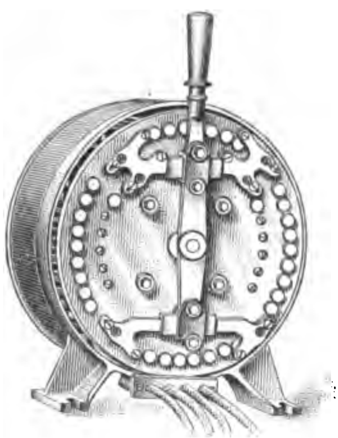


FIG. 29

70. Crane Controllers.—Figs. 29 and 30 show typical crane controllers for motors of 5 and 30 horsepower, respectively. All speed regulation is by armature control, and in each case the motor can be operated in either direction, depending on the way in which the handle is moved from the ***off-position***, or the position in which the motor circuit is open. Both controllers

are shown so arranged that the operators must stand near them, but each can be arranged for operating from a distance by means of ropes or rods. Thus, the smaller controller can be operated by ropes from the floor underneath the crane, and the larger one can be mounted outside the crane cage and operated by means of a bell-crank and a connecting-rod.

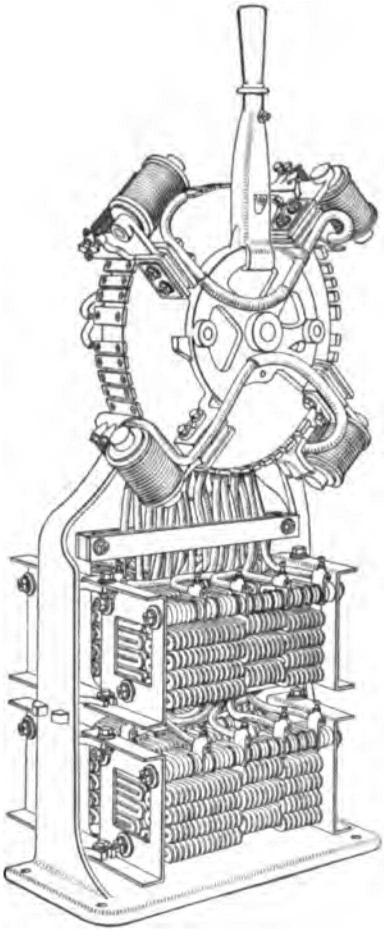


FIG. 30

71. The larger controller, Fig. 30, has two pair of moving contacts, those of each pair being connected in parallel. A magnetic blow-out coil, Fig. 31, mounted near each contact and connected in series with it sets up a strong magnetic field between the poles *a* directly through the space where arcs form between the moving and the stationary contacts; the arcs are thereby promptly disrupted, thus minimizing injury to the contacts.

72. Drum Controllers. Drum controllers arranged for adjusting armature-control resistance only are much used in connection with heavy crane and hoist service, as well as for railway work. The upper portion of Fig. 32 shows external connections of such a controller, with motors having different types of field windings. The lower portion of the figure shows the internal connections. The stationary fingers in the controller are represented by the

circles in the center; fingers R_5, R_4, etc. are connected with resistor terminals similarly lettered, and the other terminals with the armature and the line. The moving drum segments are represented by small rectangles, and the drum positions, or steps, are indicated by the vertical dotted lines *1*, *2*, *3*, *4*, *5* through these rectangles. Blow-out coils *a* are provided where necessary to prevent destructive arcing.

73. Turning the drum either way from off-position moves segments under the fingers in a way to complete a circuit through the motor and to cut out the control resistance step by step until all is out on the fifth step. The direction of current in

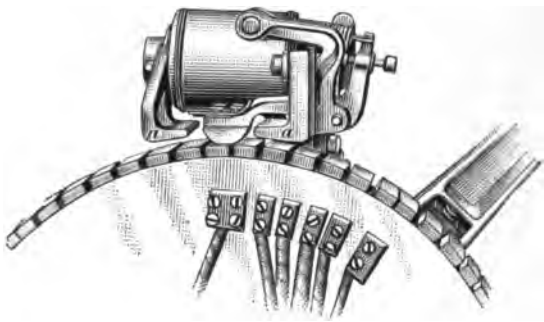


FIG. 31

the motor armature and, consequently, the direction of rotation of the motor depends on the direction in which the drum is turned.

74. Automatic Controllers.—Automatic controllers composed of magnetically operated switches, or contactors, are made for many kinds of industrial service. Shunt contactors are generally used for speed-control purposes, and the interlocking contacts are so interconnected that each switch controls the operation of the next switch in the series. By means of these switches and suitable safety devices, an operator with a simple master controller can exercise perfect control over large motors in difficult processes where starting, stopping, and reversing are frequently required. The *master controller* is a simple switching device to control the exciting current of the magnets on the contactors.

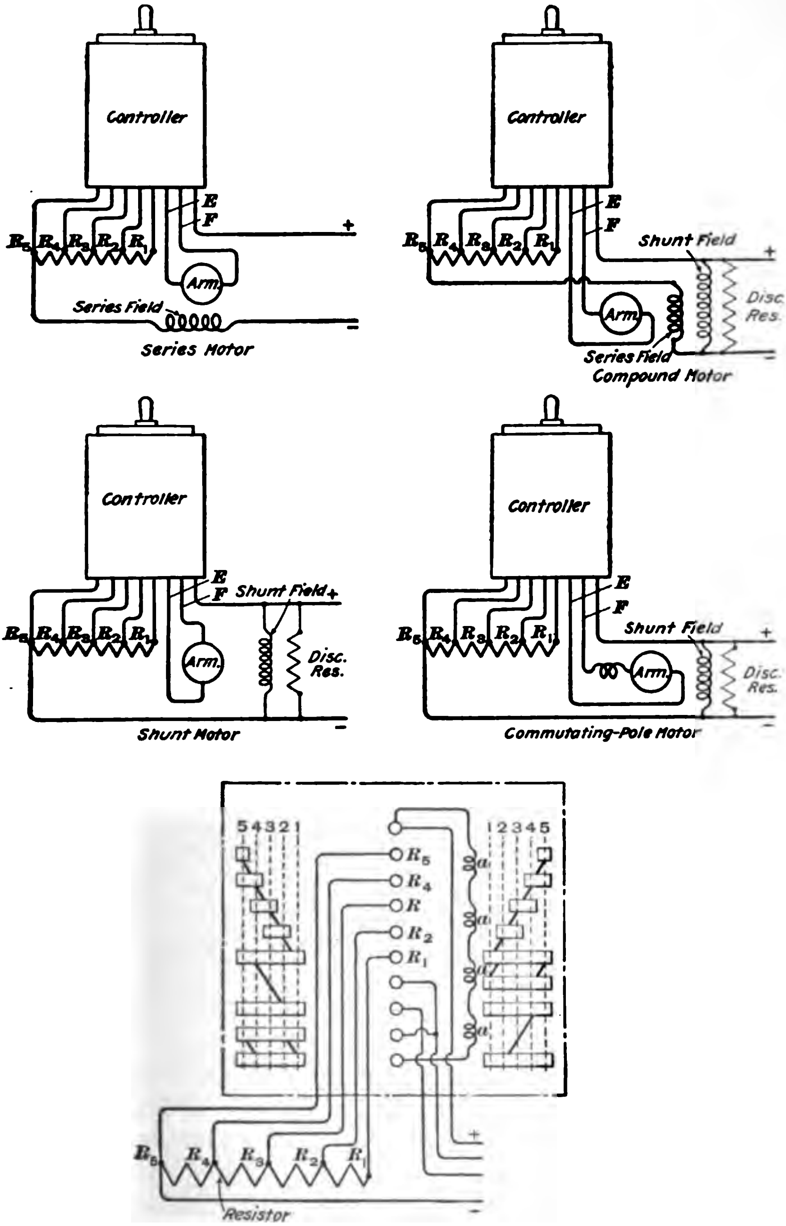

Controller
E
F
+
R5 R4 R3 R2 R1
Arm.
Series Field
Series Motor
Shunt Field
Disc. Res.
Compound Motor
Shunt Motor
Commutating-Pole Motor
5 4 3 2 1
1 2 3 4 5
R5
R4
R
R2
R1
a
Resistor

FIG. 32

RESISTANCE MEASUREMENTS

THE GALVANOMETER

ELEMENTARY TYPE

1. Description.—Measurements of resistance are usually made with the aid of instruments that, by the motion of their moving parts, indicate flow of electricity. An instrument that indicates the presence of an extremely small current is the **galvanometer,** a simple form of which is shown in Fig. 1. Inside a vertical coil *a* of wire a magnet *b* is so pivoted as to move a pointer *c* over a scale. This pointer is usually arranged at right angles to the magnet. The coil terminals are connected with the binding posts *d* on the base.

FIG. 1

2. Theory of Action.—With no current in the coil, the magnet of the galvanometer assumes a position pointing north and south, that is, parallel to the earth's magnetic flux. The coil is turned so that its plane is parallel to the direction of the earth's flux. In Fig. 2 (*a*), the coil is shown at *a*; the magnet, at *b*; and the direction of the earth's flux, by the dotted arrows. The plane of the coil, the plane of the magnet, and the direction of the earth's flux are parallel.

When there is current in the coil, the direction of the coil flux in the space near the magnet is as indicated by the dotted arrows in (*b*). If this were the only active flux, the magnet would point at right angles to the plane of the coil.

The direction of the resultant flux of the earth and the coil fluxes may, in a given case, be as indicated by the dotted arrows in (*c*). The direction, in any case, depends on the relative strengths of the two fluxes. The magnet tends to set itself parallel to the resultant flux.

The deflection of the magnet from its normal position in the earth's magnetic field will therefore depend on the strength of the earth's magnetic flux and on the strength of current in the coil. The greater this current strength the stronger will be the coil flux, the nearer will the resultant flux approach a direction at right angles to the plane of the coil, and the greater will be the deflection of the magnet and pointer.

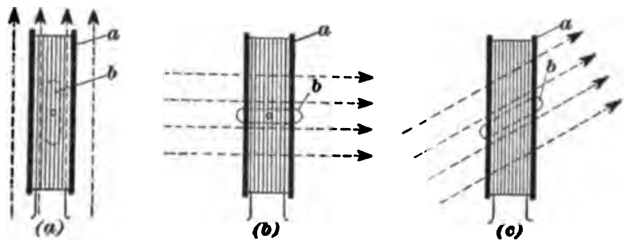


FIG. 2

Reversing the current, reverses the direction of the coil flux, thus deflecting the magnet from its normal, or zero, position in the opposite direction of rotation.

KELVIN GALVANOMETER

3. In the **Kelvin galvanometer,** which is used for the measurement of very small currents, the coil consists of a great number of turns of fine wire, and the moving part of the instrument of a few small pieces of magnetized steel strips suspended by a fine thread. A small mirror also is suspended by this thread.

D'ARSONVAL GALVANOMETER

4. Description.—In the **D'Arsonval galvanometer**, which is extensively used for electrical measurements, the magnetic field in which the moving part turns is provided by means of a permanent magnet. This type of galvanometer can usually be placed without regard to a north or south position, because the earth's magnetic flux has little influence on it.

The moving part consists of a small coil suspended by a thin, flat metal strip. The coil lies between the poles of the permanent magnet and is connected to the circuit on which measurements are to be made.

Fig. 3 shows one type of D'Arsonal galvanometer. In this instrument, the frame forms the permanent magnet and the pole pieces are located at *a* and *b*. Fastened to the back of the instrument case is a stationary iron core *c* that extends inside the movable coil *d* and thus serves to improve the magnetic circuit. A suspension strip *e* supports coil *d* and also carries a small mirror *f*. By means of this strip *e* and the wire *g* the coil *d* is connected to binding posts *h* and *i*.

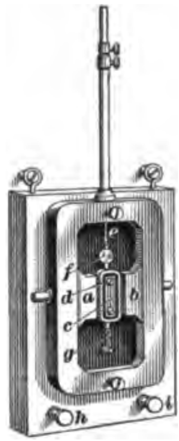


FIG. 3

5. Theory of Action.—In this type of D'Arsonval galvanometer, the suspension strip is so placed that the plane of the coil, in its no-current position, is parallel to the face of the magnet frame. Thus, current in the coil establishes a magnetic flux perpendicular to that of the permanent magnet and tends to deflect the coil until the two fluxes coincide in direction. The resulting movement of the coil twists the flat suspension, and both its resistance to twisting and the weight of the coil acting on it tend to return the coil to the no-current position. These two forces, one tending to turn the coil and the other to prevent it from turning, come to a balance, and the coil comes to rest at such a position that the deflection is proportional to the current in the coil.

Any change in the current causes a corresponding change in deflection. A reversal of the current reverses the direction of the coil flux and the direction of the deflection from zero.

METHODS OF READING DEFLECTIONS

6. A **pointer** and **scale** are often used with a galvanometer of only approximate accuracy to indicate the deflection of the instrument. In many cases such galvanometers simply serve to indicate the presence of a current and its direction. In other cases, the number of divisions on the scale between zero and the final position of the pointer indicates the current value with sufficient accuracy for the purpose intended.

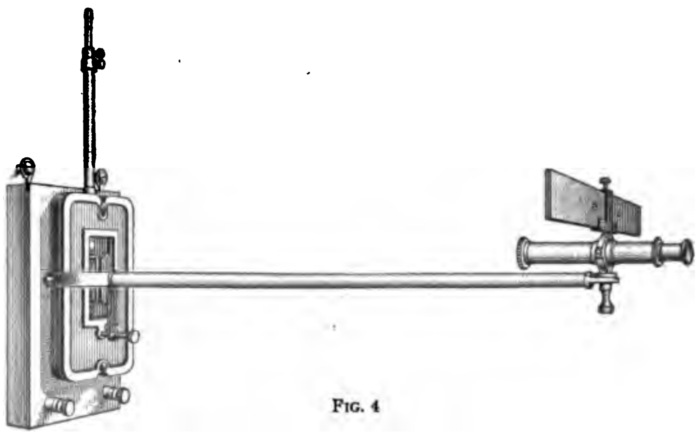


FIG. 4

7. A **telescope** and **scale** are often employed to aid in reading the deflection of the moving system of a galvanometer intended for very accurate measurements. Fig. 4 shows such an arrangement attached to a D'Arsonval galvanometer. On looking through the telescope, the operator sees in the small mirror mounted on the suspension strip of the galvanometer the reflection of a part of the scale. If the mirror turns, a different part of the scale is observed.

8. Before an attempt is made to read a deflection, the telescope and moving element are adjusted with no current

in the coil until the vertical cross-hair stretched across the glass at the end of the telescope nearest the galvanometer is in line with the reflection of the zero mark on the scale. In Fig. 5 (*a*), is shown the reflection of the scale in the mirror as viewed through the telescope under conditions of no-current and proper adjustment. The cross-hairs are indicated by the dotted vertical and horizontal lines.

When current is established in the coil, the mirror turns and the markings on the scale appear to move past the vertical cross-hair. With a steady current, the reading is the point on the scale, the reflection of which coincides with the vertical cross-hair when the coil comes to its balanced position. In Fig. 5 (*b*) is shown the reflection of the scale in the mirror as viewed through the telescope when there is a deflection of 33 divisions.

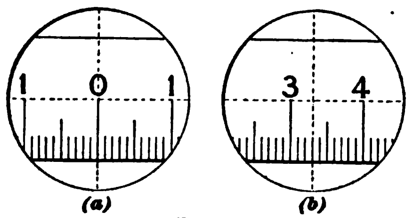


Fig. 5

With a momentary current, the general practice is to consider the reading as the point that appears in line with the vertical cross-hair at the extreme end of the throw of the coil. This is the condition when the coil has turned through its maximum angle, and is about to swing back toward its zero position.

By this method, a very small turning movement of the coil results in a deflection of several scale divisions. The galvanometer is used to measure very small currents, and therefore, the movable coil is wound with fine wire to obtain the proper coil flux.

AYRTON GALVANOMETER SHUNT

9. Connections.—A large current in the galvanometer causes a deflection that is off the scale and also may destroy the instrument. In order that the current in the galvanometer may be only a small part of the total current in the main circuit that is under test, a *galvanometer shunt* is employed.

The exterior of an **Ayrton shunt** is shown in Fig. 6. It has two line terminals *L*, and two galvanometer terminals *G*.

The connections of this shunt are shown diagrammatically in Fig. 7. The shunt consists of a resistor *0–1*, Fig. 7, all sections of which are connected across the terminals of the galvanometer *a* and some of which can be connected by leads *b c* in series with the circuit from which current is to be taken. The resistor consists of several coils connected between the contact points *1*, *.1*, *.01*, etc. The movable contact *d* is used to adjust the resistance that is included in the main circuit.

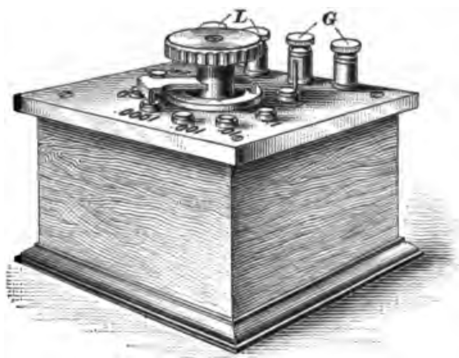


FIG. 6

10. Theory of Action.—The main current causes a drop of voltage in the part of the resistor in circuit. For example, with connections as shown in Fig. 7, the resistor sections in the main circuit are those from *0* to *.1*. The current in the galvanometer is equal to the voltage drop between *0* and *.1*, divided by the resistance of the current path *.1–1*–galvanometer-*0*. With this setting of the shunt, the section between *.1* and *1* is not included in the main circuit, but is included in the galvanometer path. If the position of *d* is changed, the relation between the main current and the galvanometer current is altered.

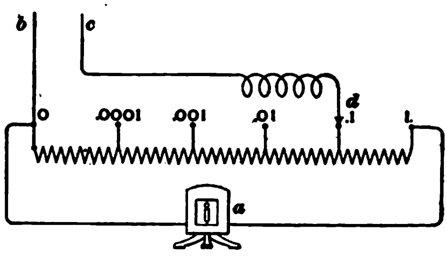


FIG. 7

The marks on the contact points indicate the relative deflections caused by a given current in the main circuit when the movable contact *d* is placed on the various points of the shunt, as compared with the

deflection when d is on *1*; thus, the deflection with d on *.1*, Fig. 7, is one-tenth the deflection obtained with d on *1*, or, differently expressed, the deflection when d is on *1* is ten times the deflection when d is on *.1*, with the same current in the main circuit.

The multiplying powers of the contact points, Figs. 6 and 7, are 1 for point *1*, 10 for point *.1*, 100 for point *.01*, 1,000 for point *.001*, and 10,000 for point *.0001*.

If, when making a test, it is necessary to use one or more points on the shunt to obtain readings on the scale, the deflections should be multiplied by the multiplying power for those points in order that there may be a common base for comparison of current conditions in the main circuit. This base is the equivalent deflections that would have been obtained if it were possible to use point *1* for all tests.

The main circuit is opened by moving the switch arm, Fig. 6, to the point marked *INF*.

EXAMPLE.—If, when using an Ayrton shunt in connection with a galvanometer, one main current causes a deflection of 50 divisions when the contact d is on point *1*, Fig. 7, and another current causes a deflection of 45 divisions with d on point *.1*, how do the two currents compare in strength?

SOLUTION.—A deflection of 45 with d on *.1* is equivalent to $10 \times 45 = 450$ divisions with d on *1*. Therefore, the strength of the second current is $\frac{450}{50}$, or 9 times that of the first. Ans.

CONDUCTOR RESISTANCE

WHEATSTONE BRIDGE

11. Connections.—Several methods are available for measuring electrical resistance, one being by means of the **Wheatstone bridge.** Many forms of Wheatstone bridge are in use, but all operate on the general principles explained by means of the diagram shown in Fig. 8.

Known resistances M, N, and P and the unknown resistance X (to be measured) are arranged as shown to form two paths between two points a b of a circuit. A galvanometer is con-

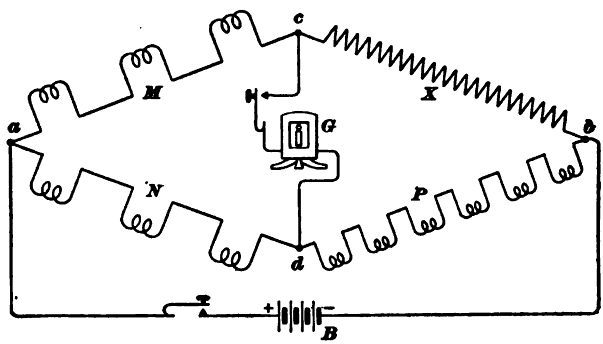


FIG. 8

nected between the terminal c of the unknown resistance X in one path and the terminal d of the adjustable resistance P in the other path.

12. Theory of Action.—The resistances of M, N, and P are adjusted until no deflection of the galvanometer occurs, when the battery key and the galvanometer key are pressed. The bridge is then *balanced.*

No deflection indicates no current in the galvanometer, and there is no current because there is no difference of potential between the terminal points c and d of the galvanometer.

There must be, therefore, the same current I_c in M as in X, and the same current I_d in N as in P, that is, there is no exchange of current from one path to the other through the galvanometer.

The points a and b are common to both paths; therefore, to have no difference of potential between c and d, the drop of potential $M\,I_c$ in M must equal the drop $N\,I_d$ in N, and the drop $X\,I_c$ must equal the drop $P\,I_d$; that is,

$$X\,I_c = P\,I_d$$
$$M\,I_c = N\,I_d$$

By dividing the first equation by the second,

$$\frac{X\,I_c}{M\,I_c} = \frac{P\,I_d}{N\,I_d}, \text{ or } \frac{X}{M} = \frac{P}{N}$$

and

$$X = \frac{M}{N}P,$$

which is the fundamental equation of the Wheatstone bridge.

13. Names of Bridge Arms.—The arms M and N, Fig. 8, are called *ratio*, *bridge*, or *balance arms* and they usually have an equal number of resistors of corresponding resistance values. Usually only one resistor in each balance arm is active during a test. The arm P is called the *rheostat arm* and it is provided with a large number of resistors of different resistance values, one or more of which may be active. The resistors are in the form of coils, arranged within a box and connected to terminals on the top of the box for adjusting the resistances of the arms. A switch key in the battery circuit and another in the galvanometer circuit serve to close these circuits when making a test.

14. Description of Dial-Switch Bridge.—In Fig. 9 is shown a Wheatstone bridge set with dial switches for adjusting the resistance in the rheostat arm; the connections of a bridge of this general type are shown in Fig. 10. The resistors in the rheostat arm are in groups, and each group is controlled by means of a dial switch. The coils in each group are connected in series, as are also the groups. Each switch arm serves to

connect any number of the coils in its group into the active circuit, the number being indicated by the marking on the contact point on which the arm rests.

Each resistor of a group has the same resistance. The values, .1 ohm, 1 ohm, 10 ohms, 100 ohms, and 1,000 ohms, are marked on the switch arms. The active resistance of each group is found by multiplying the number on the active contact point by the resistance of each active coil of that group. For example, the rheostat arm, Fig. 10, has a resistance of 3,217.7 ohms.

15. The resistance of either of the ratio arms M or N, Fig. 10, is adjusted by placing a metal plug in the hole between

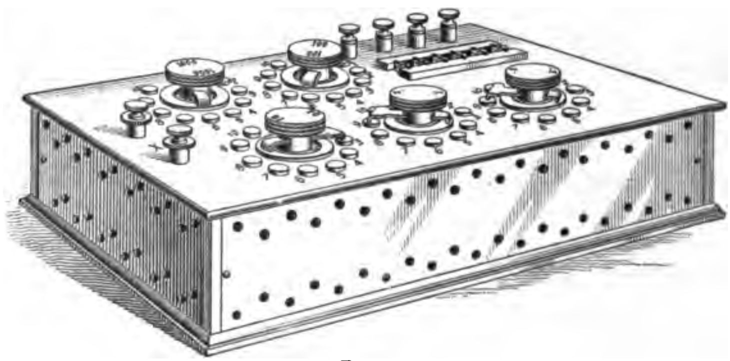


FIG. 9

the terminal of the resistor selected and either bar M or N. The resistance of each coil is marked on its terminal. Two plugs are shown in place. A 10-ohm resistor is in arm M and a 1,000-ohm resistor in arm N. If, with the resistance adjustment shown for M, N, and P, the bridge is balanced, the value of $X = \frac{M}{N} P = \frac{10}{1,000} \times 3,217.7 = 32.177$ ohms.

In Fig. 10, a separate galvanometer and a separate battery are shown. In portable bridges, both of these devices are placed within the case of the bridge set, and a pointer and scale are used to indicate movement of the galvanometer.

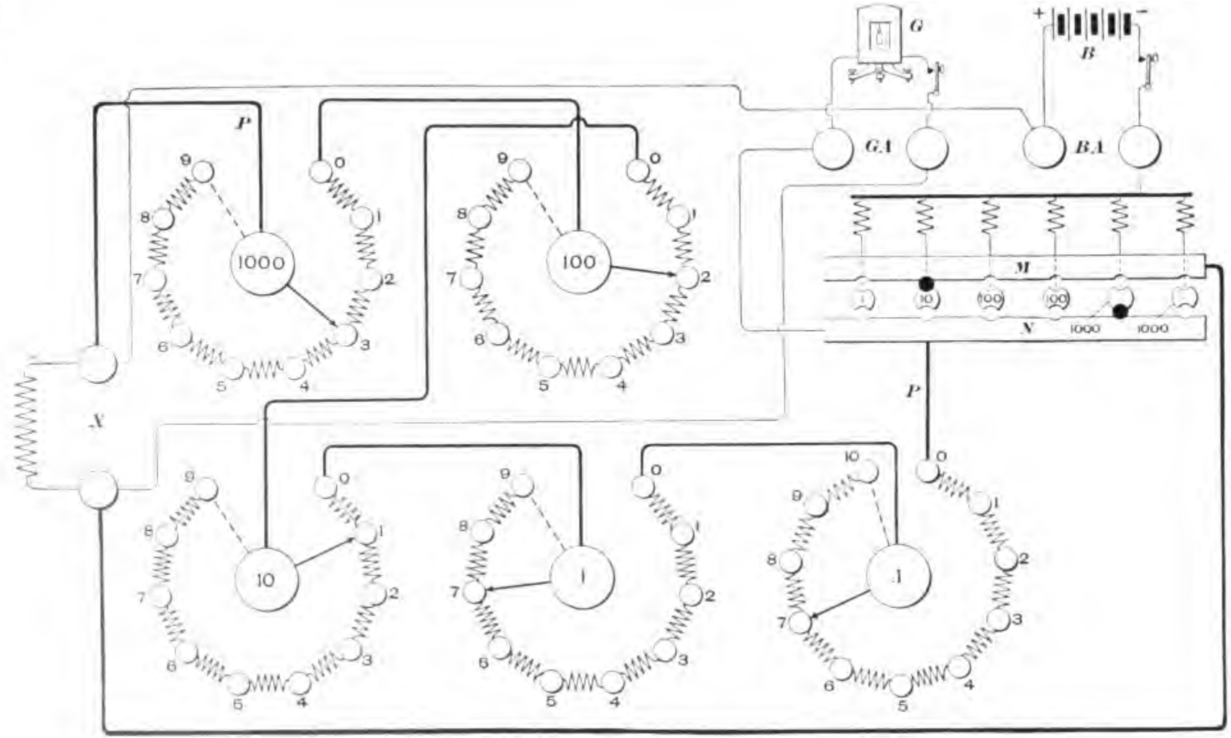


FIG. 10.

16. Operation.—The following directions relate to the use of the bridge set shown in Fig. 10, but they apply in general to all Wheatstone bridges:

The wire, coil, or other device to be measured is connected to terminals X. If long leads are used to connect the device to the bridge, their resistance should be determined and subtracted from the result of the test on the leads and device.

TABLE I

SETTING THE RATIO ARMS

Unknown Resistance, In Ohms	Resistance, In Ratio Arms		P Equals	X Equals
	M	N		
Below 10	1	1,000	$X \times 1{,}000$	$\frac{P}{1{,}000}$
10 to 100	10	1,000	$X \times 100$	$\frac{P}{100}$
100 to 1,000	100	1,000	$X \times 10$	$\frac{P}{10}$
1,000 to 10,000	1,000	1,000	X	P
10,000 to 100,000	1,000	100	$\frac{X}{10}$	$P \times 10$
100,000 to 1,000,000	1,000	10	$\frac{X}{100}$	$P \times 100$
1,000,000 to 10,000,000	1,000	1	$\frac{X}{1{,}000}$	$P \times 1{,}000$

The distant ends of the leads should be connected together when testing the lead resistance.

17. The approximate resistance of the device may be known or it can be determined by a rough test, after which the ratio arms can be adjusted as indicated in Table I.

18. Let it be assumed that the resistance of the device to be measured is known to be approximately 30 ohms. This

number lies between 10 and 100; therefore, according to Table I, arm M should have a resistance of 10 ohms, arm N, a resistance of 1,000 ohms, and the rheostat arm P, a resistance of $30 \times 100 = 3{,}000$ ohms, approximately.

In this case the procedure would be as follows: Set the plugs in the ratio arms as shown in Fig. 10; also, set the 1,000 dial switch arm on contact *3* and the other arms on contacts *0*. Next, press the battery key and then the galvanometer key and note to which side of its no-current position the moving element of the galvanometer turns. Release the galvanometer key and then the battery key, and add 500 ohms to the rheostat arm circuit by placing the 100-dial switch arm on contact *5*, making 3,500 ohms in this circuit. Then, note the direction of the deflection of the galvanometer when the keys are pressed, taking care to press the battery key first. If this deflection is opposite in direction to the first deflection, it indicates that 500 ohms was too large an addition.

According to the last column of Table I, the resistance of the device is between $\frac{3{,}000}{100}$ and $\frac{3{,}500}{100}$ ohms, and a comparison of the deflections will indicate which value of resistance is nearer correct.

Adjustments of the dial switches should continue until the deflection is zero, when the keys are pressed. The higher resistance coils should be used for coarse adjustments and the lower resistance coils for fine adjustments. The effect of each change on the deflection indicates whether the change is in the right direction and whether it is too large or too small. A few trials will bring the correct adjustment, and the unknown resistance can then be determined, as indicated in the last column of Table I. If the adjustments are as shown in Fig. 10, the resistance X is $\frac{P}{100} = \frac{3{,}217.7}{100} = 32.17$ ohms.

19. If the resistance of the device is not even approximately known, each ratio arm should be set for 1,000 ohms and the resistance of arm P should be adjusted until two fairly close adjustments that give small deflections in opposite

directions are found. Since, with this setting of the ratio arms, $X=P$, the approximate resistance value of X is read directly from the setting of P.

Suppose that with the 1-ohm dial switch on contact *9* (9 ohms) the deflection is one way, and with the 10-ohm switch on point *9* (99 ohms) the deflection is the other way; then, the resistance of X is between 9 ohms and 99 ohms. The ratio arm should then be set according to Table I, and a final test made.

If the even setting of the ratio arms does not produce the approximate value of X, it will be necessary to try the next setting of these arms indicated in Table I, either for higher or lower values of X, as the case demands.

SLIDE-WIRE BRIDGE

20. Connections.—For measuring low resistances, a modified form of the Wheatstone bridge, known as the **slide-wire, or meter, bridge** is often used.

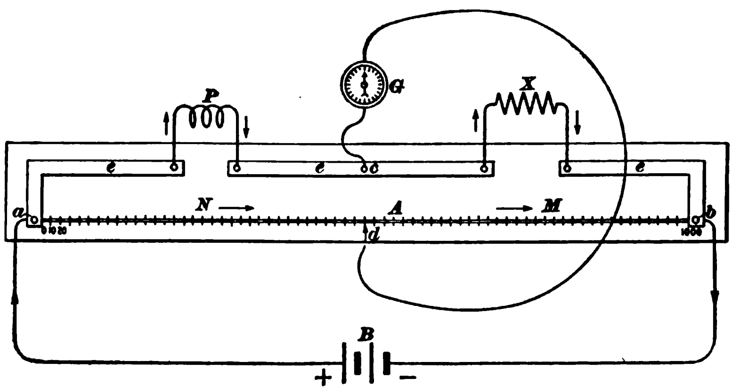


Fig. 11

A diagram of its connections is shown in Fig. 11. The parts are mounted on the board A, and a German-silver wire $a\,b$ of uniform resistance is stretched between large copper blocks, to which the terminals of battery B also are connected. The wire lies over a scale that is divided into 1,000 equal divisions. Point c and slider d form the terminals of the circuit of the galvanometer G.

A switch key (not shown) may be used to close the battery circuit during a test; or, the battery may be connected between c and d and the galvanometer between a and b. In the latter case the battery circuit is closed by touching d to the slide wire during a test. The object of either method is to limit the time that the battery is active.

The resistance of coil P is known, and X represents the resistance to be measured. The connecting copper strips e have very low resistances. The resistances are connected in the form of a Wheatstone bridge, as is indicated by a comparison of the connections M, N, P, and X, Figs. 8 and 11.

21. Names of Arms.—The known resistance P forms the ***known arm;*** the resistance X to be measured is the ***unknown arm;*** and the two arms $a\,d$, or N, and $d\,b$, or M, formed on the wire $a\,b$ by the slider d, are the ***ratio arms***, which are sometimes called the ***proportion arms***.

The value of P is usually .1, 1, or about 10 ohms. The resistance coil used in arm P should be of about the same resistance as the device to be tested.

22. Operation.—By sliding d along the wire $a\,b$, some point on the wire can be found at which no deflection occurs, thus indicating a balanced condition. As the wire $a\,b$ is of uniform resistance throughout its length, scale divisions can be used instead of resistance values to express the ratio of the arms M and N. For example, suppose that P is 1 ohm and that the balance point of d is found to be 400 divisions from a and 600 divisions from b. Arm N is then 400 divisions and arm M is 600 divisions. Substituting the known resistance value of P, which is 1 ohm, and the known division values of the arms M and N in the bridge formula $X=\frac{M}{N}\times P$, $X=\frac{600}{400}\times 1$ $= 1.5$ ohms.

THE OHMMETER

23. Connections.—The **ohmmeter** is an instrument from whose scale the value, in ohms, of the resistance that is being measured can be read directly. Its principal of operation is similar to that of the slide-wire bridge.

One form of ohmmeter is shown in Fig. 12 (*a*), and its connections are shown diagrammatically in (*b*). By inserting the plug *P* in one of the four terminals marked *Brown*, *Blue*, *Red*, and *Black*, the resistance coil corresponding to that marking is made the known arm. The slide wire is in two lengths from *A* to the metal block *B* and from *B* to *C*. The numbers printed on the scale located below the wire are also in four colors, to agree with the terminals. The slider is shown at *S*, and the terminals for the unknown resistance *X*, at *A* and *D*. Instead of a galvanometer, use is made in this device of a telephone receiver *T*, which is connected between *D* and *S*. A small key switch in the battery circuit is shown at *K*.

The telephone receiver usually consists of two small coils of wire mounted on iron cores, near the front ends of which is placed a thin iron disk. When current passes through the coils, this disk is attracted and a click is heard, provided the receiver is held close to the ear. When no current passes, no sound is made.

The connection of the ohmmeter, as indicated in Fig. 12 (*b*), should be compared with the slide-wire bridge connections shown in Fig. 10. These connections are practically similar.

24. Operation.—To measure an unknown resistance *X*, proceed as follows: First, connect resistance *X* to posts *A* and *D*, Fig. 12. Put plug *P* in the terminal marked *Brown*, place telephone to the ear, press the key *K*, and tap the slider *S* along wire *A B C* until the click of the telephone ceases or is at a minimum. Read the resistance of *X* directly from the brown number under the balance point on wire *A B C*.

If this point is found to be at a place on the scale where close readings are difficult, place the plug in the blue terminal, find the new balance point, and read from the blue scale. If necessary to

advance the plug to the red or the black terminal, use the scale markings corresponding in color to that of the active terminal.

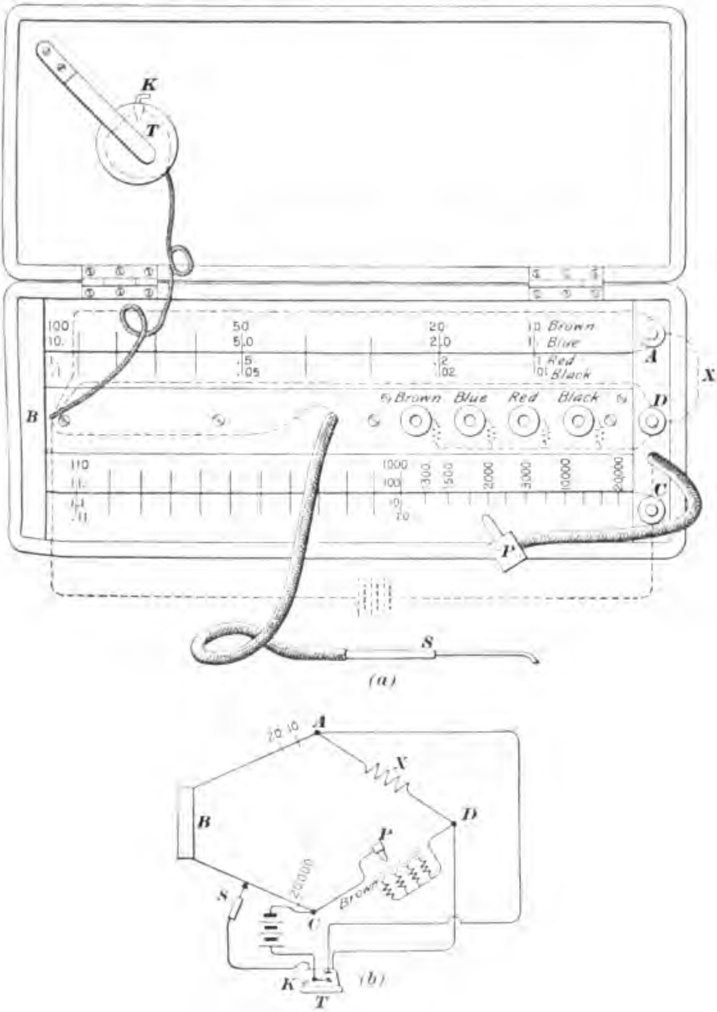


FIG. 12

If there is a short space on the wire ABC where no sound is heard, consider that the balance point is at the centre of this space.

INSULATION RESISTANCE

GENERAL CONSIDERATIONS

25. Necessity for Insulation Resistance.—In order to confine electricity to intended paths, these paths must be *insulated;* that is, they must be surrounded with materials having a resistance so high that electricity cannot escape through them. Mica, glass, porcelain, rubber, treated cloth, oils, varnish, etc., are some of the materials used; some in the forms of covers for the conductors and others in the form of supports for either bare or insulated conductors.

26. Length and Cross-Sectional Area of Path Through Insulation.—The resistance of the insulation depends on the material, on the length of the leakage path through it, and on the cross-sectional area of this path. The length of the leakage path in the case of a submarine cable is the distance between the conductor and the metal covering, or sheath, placed outside of the insulation, and which is in contact with the water. Since the current can leak from all points on the conductor to the sheath, the cross-sectional area of the leakage path in the cable is equal to the mean circumference of the insulation multiplied by the length of the cable. With a long cable, this area is enormous and explains why, even with good insulating material, an appreciable leakage current may be present.

THE MEGGER

27. The **megger,** Fig. 13, is a device used to indicate directly the insulation resistance of cables, motor and generator windings, line circuits, etc. When the resistance to be measured is connected to the binding posts on the side of the case and the crank is turned, the pointer moves over the scale,

shown near the lifted cover to a position that indicates the value of the resistance.

28. Description.—In Fig. 14 is shown the megger with its case removed. A small direct-current generator *a* operated through gearing by means of the crank *b* can be made to produce an electromotive force of from 100 to 1,000 volts, depending on the winding of the armature and on the speed. Four permanent bar magnets, two of which are shown at *c*, furnish the necessary magnetic flux for the generator at one end and the flux in which the moving element of the measuring instrument at the other end of the megger turns. A pointer *d* is attached to the moving element.

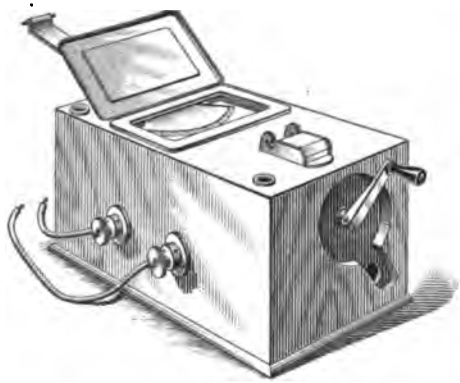


FIG. 13

29. Connections.—In Fig. 15 are shown the internal and external connections for testing the insulation of a cable. The direct-current generator is shown at *a*, and the measuring instrument of the D'Arsonval type at the left. The moving element of the instrument consists of three coils *b*, *c*, and *d* attached to a shaft that moves the pointer. Coils *b* and *c* and a resistor *e* are in series directly across the generator terminals. They carry a current proportional to the generator electromotive force and independent of the condition of the insulation.

The two coils *b* and *c* are rigidly attached to each other in one plane, and this plane is at a small angle from the plane of coil *d*. The outer side of coil *c* projects so far beyond the field of the permanent magnet as to be little affected by it, and the inner side of coil *b* is shielded by the iron core *f*. Coil *b* is wound in the opposite direction from coil *c*, so that if there is a stray magnetic flux from, for instance, a near-by generator,

the turning action of one coil that it may set up, is compensated by the opposite turning action of the other coil. The parts of coils *b* and *c* that are active in moving the pointer are the sides between core *f* and the upper pole piece.

Coil *d* is in series with the insulation that is being measured and the resistor *g*, and therefore carries the same current as the insulation.

30. Theory of Action.—Two paths are available for the generator current—one through coils *b* and *c* and the resistor *e* and the other through coil *d*, resistor *g*, and the insulation.

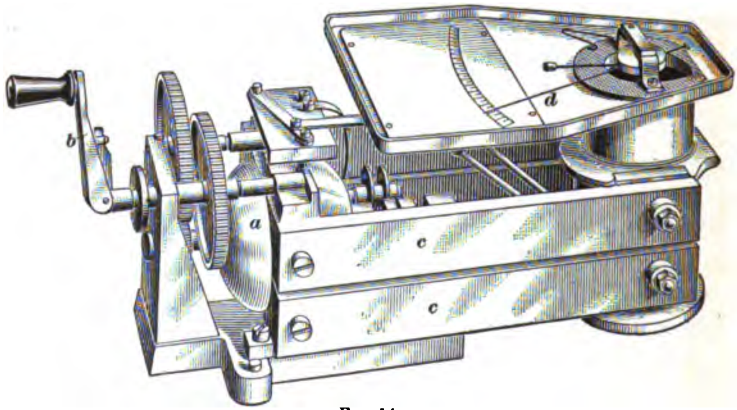


Fig. 14

The current in coils *b* and *c* tends to turn the moving element in a counter-clock wise direction.

With little or no current in coil *d*, the current in coils *b* and *c* will move the pointer to the *INF*. position on the scale. This indicates that the insulation resistance is ***infinitely high***.

When the insulation is not perfect and there is current through it and coil *d*, the turning force of this coil is increased and the pointer will take up some intermediate position between *0* and *INF*. At this position of the moving element, the turning force of coils *b* and *c* is balanced by the turning force of coil *d*. The poorer the insulation, the greater the current through coil *d*, and the nearer *0* the deflection becomes. There are no control springs on the moving element, the final

position depending on the balance of the opposing turning movements.

31. Constant-Pressure Megger.—When the circuit under test contains a considerable amount of electrostatic capacity, the testing electromotive force should remain constant, as otherwise steady readings will not be obtained. In the constant-pressure megger, the generator is driven through a friction clutch that releases by centrifugal action if the normal handle speed of 100 revolutions per minute is exceeded.

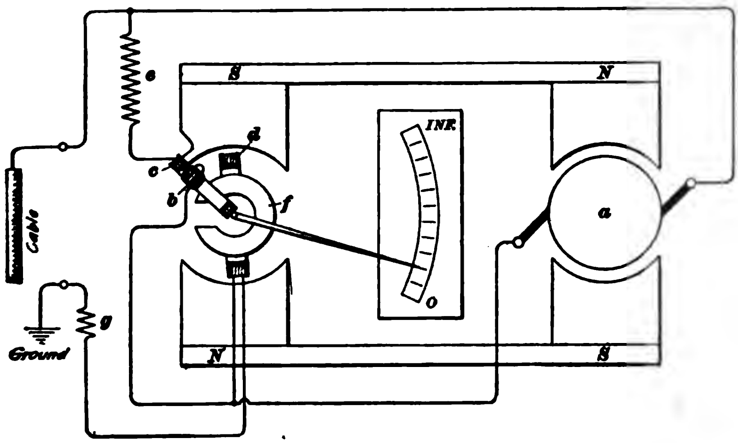


FIG. 15

32. Variable-Pressure Megger.—In the variable-pressure megger, the friction clutch is omitted and the electromotive force generated by the armature may be varied by turning the handle at different speeds. When the insulation resistance to be measured is high and little electrostatic capacity is present, the higher electromotive force that may be generated in the variable-pressure megger is sometimes desirable in order to force an appreciable current through the insulation.

33. Insulation Resistance per Mile From Reading of Megger.—The readings of the megger give the insulation resistance for the entire length of cable under test. If the insulation resistance per mile is desired, the megger reading should be multiplied by the length of the cable in miles.

DIRECT-CURRENT MEASURING INSTRUMENTS

DESCRIPTION OF INSTRUMENTS

GENERAL CLASSIFICATION

1. Instruments are available for the measurement of practically all electrical quantities. These instruments may be classified according to: (1) the kind of current in the circuits on which they are used, as *direct-current* or *alternating-current instruments;* (2) the service for which they are intended, as *switchboard* or *portable instruments;* (3) their principles of operation, in direct-current work, as *moving-iron*, *D'Arsonval*, *electrodynamometer*, *electrostatic*, and *hot-wire*, *instruments;* and (4) the methods of showing the results of measurements, as *indicating*, *recording*, or *integrating instruments*. Instruments of the integrating type are described in *Watt-Hour Meters*.

MOVING-IRON INSTRUMENTS

2. **Repulsion Movement.**—Fig. 1 shows a **Weston eclipse direct-current ammeter** of the switchboard type. This instrument depends for its operation on the magnetic repulsion between a stationary vane *a* of soft iron and a movable vane *b* of soft iron, both of which are placed within the fixed magnetizing coil *c* and are thereby magnetized in the same direction when current is established in the coil. Like

poles repel each other, and this action causes a movement of the movable vane *b*, its shaft, and the attached pointer *d*.

The movement is damped, or retarded, by a vane *e* that is attached to the shaft of the instrument and turns in a covered chamber *f*. There is but little clearance between the edges of the vane and the sides of the chamber. Two small vent holes in the cover of the chamber, only one of which is shown, allow the air to pass in or out, according to the movements of the vane. By this means the pointer comes to rest at its proper deflection almost immediately. The instrument is said to be *dead-beat*, and this feature materially assists the rapidity with which measurements are taken.

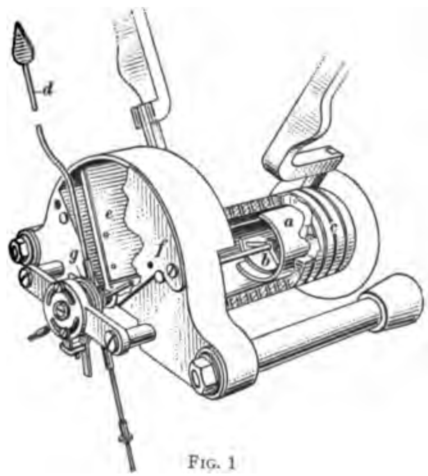


FIG. 1

A spiral control spring *g* opposes the torque acting on the shaft and returns the moving element to zero position when the torque ceases. The coil *c* carries the line current, because it is connected directly in series with one of the line wires. The reading position of the pointer is at the point of balance of the magnetic forces and the force of the control spring.

3. Inclined-Coil Instrument.—The **Thomson inclined-coil ammeter**, also of the moving-iron type, is shown in Fig. 2. This instrument has a stationary coil, shown in section at *c*, mounted on a frame *s* and inclined 45° to a vertical shaft through its center. Within the coil, and mounted on the shaft at an angle of 45° to it, are one or more soft iron vanes *v*. The shaft carries a pointer *p* that moves over a scale *S*.

With no current in the instrument, the pointer is at zero position and the plane of the vane is at an angle to the axis

of the coil. When current is established, the vane tends to turn to a position in which its plane is parallel to the coil flux. The long arrows indicate the direction of the coil flux, and the dotted lines near v', the position of the vane when its plane is parallel to the flux. The moving element turns until the magnetic forces are balanced by the force of the control springs a and a'; and the reading is then indicated by the pointer and scale.

In one form of this instrument, the damping effect is due to the eddy currents set up in an aluminum disk mounted on the shaft in such a position that parts of the disk are between the poles of permanent magnets. When the moving element

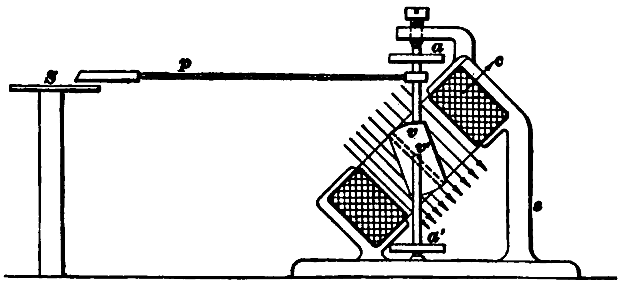


FIG. 2

turns, the generator action of the disk and magnets serves to retard the motion and to make the instrument dead-beat.

4. Application of Operating Principle.—The principle of operation just described for the Thomson inclined-coil ammeter is employed in some voltmeters and ammeters for either direct-current or alternating-current service. The coil of the voltmeter consists of many turns of fine wire and is connected across the circuit with or without a resistor in series. The ammeter coil consists of a few turns of large conductor, and for the measurement of small currents it is often connected directly in series with one of the line wires of a circuit. To prevent stray magnetic fluxes of neighboring conductors from affecting the instrument, the working parts are often enclosed in an iron case.

INSTRUMENTS OF THE D'ARSONVAL TYPE

GENERAL DISCUSSION

5. Construction.—The D'Arsonval principle is used extensively in direct-current instruments for portable and switchboard service because it permits of substantial construction and a high degree of accuracy in measurements. Such instruments are based on the same principle as the galvanometer of the D'Arsonval type, but they are not suitable for alternating-current measurements.

The **Weston direct-current ammeter,** an exterior view of which is shown in Fig. 3, is an instrument of this type. Fig. 4 shows some of its working parts, indicating the relative positions of the permanent-magnet pole pieces, the stationary cylindrical core, the brass plate supporting this core, the movable coil, and the control springs.

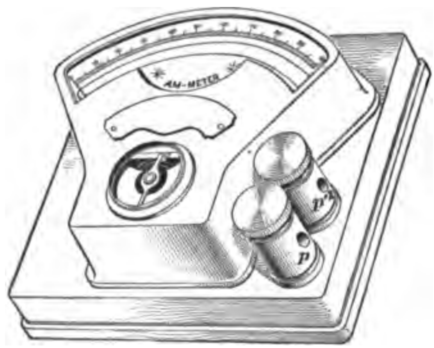


FIG. 3

Fig. 5 shows the magnetic circuit of this instrument. The permanent magnet *A* has soft-iron pole pieces *P* fastened to it by screws *S*, and the stationarv soft-iron core *C* is supported by a screw *M* passing througn a brass plate *B*. Since the diameter of the core is smaller than the bore of the pole pieces, two narrow air gaps are formed, and in these gaps are placed the vertical sides of the movable coils, Fig. 4. The coil is thus subjected to the action of a nearly uniform magnetic flux, which passes from pole to pole across the air gaps and the core.

The movable part of this instrument is shown in Fig. 6. It consists of a rectangular coil *C* of fine wire wound on a

bobbin, either of aluminum or copper, that is suspended vertically between two delicate jeweled bearings. Two flat control springs S oppose the tendency of the coil to rotate, and they also serve to conduct current to and from the suspended coil. A thin aluminum pointer P attached to the coil moves over a scale as the coil turns, thus indicating the deflection.

6. Operation.—In instruments of the D'Arsonval type, current in the movable coil reacts with the flux from the magnets and tends to turn the coil to a position in which its flux

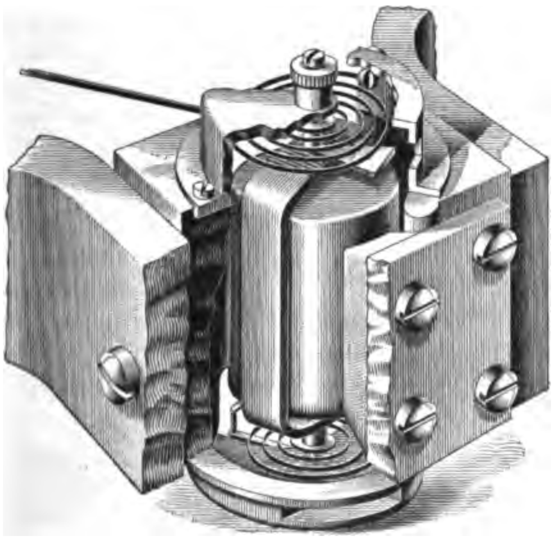


FIG. 4

will coincide in direction with the flux of the permanent magnet. The coil will come to rest at a position in which the torque due to the magnetic forces is balanced by the torsion of the control springs. The scale is so divided and marked as to read in either amperes or volts.

The strength of the magnetic flux in the air gaps is so nearly uniform that the deflection is closely proportional to the current in the coil, thus making the scale division of very nearly uniform length, as shown in Fig. 7. This scale is from a 150-ampere ammeter and is three-fourths full size.

7. Parallax.—In order to secure great accuracy of observation, a mirror is often set in the scale card, as indicated in Fig. 3. Thus, if the observer stands over the instrument in such a position that the pointer either completely obscures its image in the mirror or appears to lie midway in the image, error due to *parallax*, or reading of the deflection sidewise, is avoided, because the line of vision is then practically at right angles to the plane of the coil.

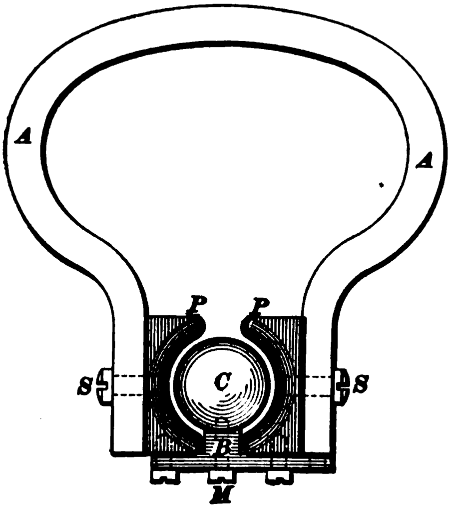


FIG. 5

8. Method of Making the Instrument Dead-Beat.—When the metal bobbin on which the coil is wound moves across the magnetic flux, the electromotive force thereby set up causes current in the bobbin opposite in direction to the current in the coil. Since the current in the coil causes the motion, the current in the bobbin opposes the motion; and, as this tendency exists only when the bobbin is moving, it has the effect of retarding or dampening the motion of the needle, thus bringing it quickly to rest at the proper point. The friction of the coil pivots on the bearings is so slight that it has practically no effect on the position that the needle will take. This is shown by the fact that the needle after having been deflected by a current will respond to very minute variations in that current; that is, the instruments are very *sensitive*.

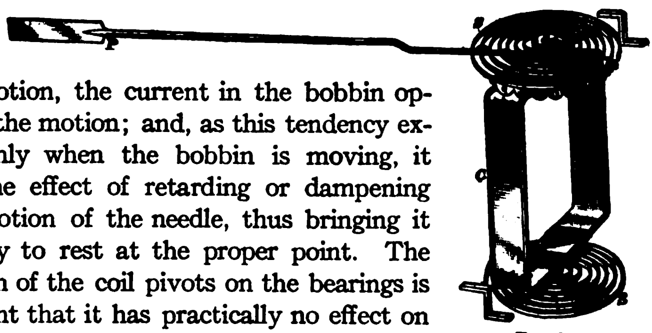


FIG. 6

9. Similarity in Construction of Ammeters and Voltmeters.—The general features of construction are practically the same for direct-current ammeters and voltmeters of the D'Arsonval type. If the instrument is designed for a voltmeter, a high resistance, located in the back of the case, is connected in series with the movable coil, which is wound with a large number of turns of very fine wire. If it is designed for an ammeter, the coil has fewer turns of coarser wire, and for all coils except those intended for very small currents the coil is connected in parallel with a short, thick piece of copper or some alloy, called an *ammeter shunt*, so that only a small part of the current being measured passes through the coil. The shunt of an ammeter intended for moderate current is often placed in the case of the instrument.

10. The joint resistance of the shunt and the coil of an ammeter is extremely low, and the resistance of a voltmeter

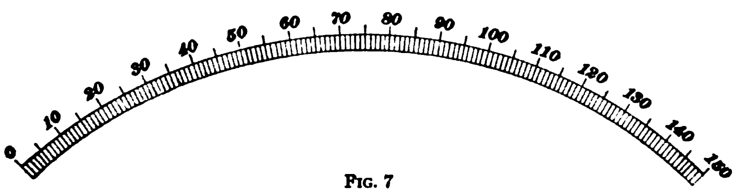


Fig. 7

coil is high; therefore, very little energy is required to operate either instrument. For example, a 15-ampere Weston ammeter has an internal resistance of .0022 ohm; when measuring a 10-ampere current, the drop ($I\ R$) is .022 volt, and the power ($I\ E$) = .22 watt, or about $\frac{1}{3400}$ horsepower. Again, the resistance of a 150-volt voltmeter is about 18,000 ohms. When measuring 110 volts, the instrument takes $\frac{110}{18{,}000} = .0061$ ampere, and the power is $.0061 \times 110 = .671$ watt, nearly, or about $\frac{1}{1100}$ horsepower.

The moving coil usually consists of fine copper wire, but the resistance wire in a voltmeter and, in some cases, the shunt of an ammeter are made of an alloy that changes very little in resistance if the temperature of the alloy changes; thus, moderate changes in the temperature of either the instrument

or the ammeter shunt do not perceptibly affect the accuracy of the readings.

11. Astatic Instruments.—The magnetic flux set up by current in a neighboring conductor may affect the accuracy of an instrument unless means are taken to counteract the influence of such stray fluxes. In any case, it is advisable, if possible, to keep the instruments away from conductors carrying large currents. An instrument is called *astatic* when the working parts are so arranged that stray magnetic fluxes have practically no effect on the readings.

An astatic arrangement is indicated in a conventional manner in Fig. 8. The instruments usually have two movable

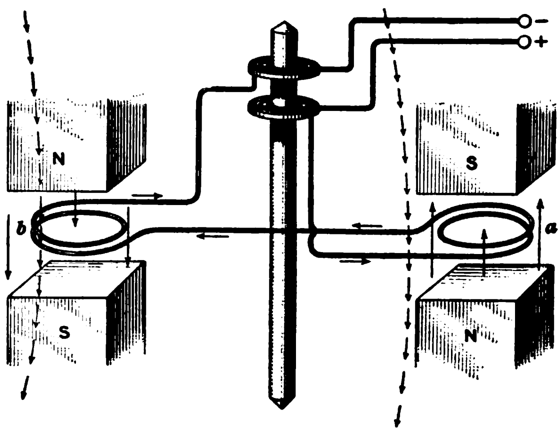


FIG. 8

coils a and b that are connected in series and are attached to a single shaft. Each of these coils is placed in a magnetic field, but the fluxes of these fields are in opposite directions; also, the two movable coils are so wound and connected that the direction of current in coil a is opposite that in coil b; therefore, the influence of a current in the coils is to swing them in a common rotative direction about the axis represented by the vertical rod. The flux of each coil agrees in direction with that of the flux between the nearest pair of poles. Therefore, the coils tend to be drawn into the spaces

between the poles from their zero, or no-current, position outside of these spaces. In Fig. 8 the coils are shown between the poles in maximum-current position.

12. If a stray magnetic flux, however, passes through both coils in the same direction, as indicated by the curved dotted lines in Fig. 8, the interaction between the stray flux and the coil fluxes tends to turn the coils in opposite directions. The effect of the stray field on the rotation of the moving element is therefore practically neutralized.

Astatic instruments are much used on switchboards that must necessarily be located in proximity of large current-carrying conductors. In some cases, additional protection from stray fluxes is provided by means of an iron instrument case.

13. In some types of astatic instruments, the magnetic field in which the moving element turns is provided by permanent magnets, electromagnets, or solenoids. In case electromagnets or solenoids are used, the error due to variations in the exciting current of the electromagnet or solenoid is reduced by mounting small pieces of iron on the shaft of the moving element in such positions that when the coils are moving toward the spaces between the poles, the iron pieces are being forced away from the poles. This action tends to retard the motion of the coils. If the exciting current and the flux decrease, the torque on the moving coils decreases, but at the same time the retarding effect of the iron pieces is lessened. If the exciting current and the flux increase, the coil torque increases, and so does the retarding effect of the iron pieces.

AMMETERS AND SHUNTS

14. Connections.—In Fig. 9 are shown the connections of a high-reading ammeter *a* and its shunt *b*. The shunt is connected in the circuit, and the ammeter is connected with the shunt terminals. Care should be taken that the positive terminal of the ammeter, usually marked +, is connected to the positive terminal of the shunt, which is at the end of the

shunt through which current enters. The current through the ammeter is proportional to the voltage drop in the shunt, and this drop is proportional to the current in the circuit. An instrument that indicates current strength when connected with the terminals of such a shunt is essentially a *millivoltmeter* with a scale reading in amperes.

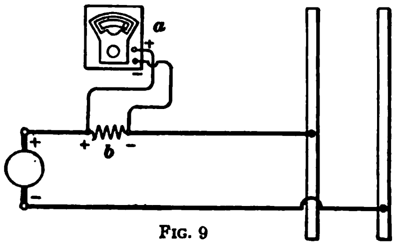


FIG. 9

Fig. 10 shows such a shunt consisting of terminals *a*, and flat strips *b*. Flexible leads *c* serve to connect the shunt with the instrument. All such shunts have low resistance and large radiating surface, and are made of an alloy, the resistance of which remains practically constant at all working temperatures.

Each shunt is made for use with a given instrument; therefore, care should be taken to see that the shunt number is the same as that of the instrument with which it is used. The connecting wires supplied with the shunt should be used; any change in their length or the substitution of other wires may affect the accuracy of the readings.

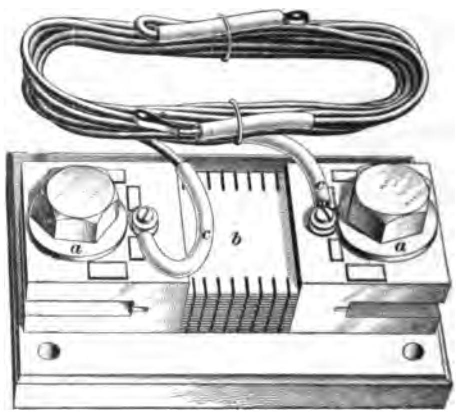


FIG. 10

15. Increasing the Range of an Ammeter.—In many cases a standard millivoltmeter is used as an ammeter; then, one or more shunts are adapted for use with the instrument, so that the range of the instrument may be extended to suit the conditions of work. A millivoltmeter thus used may be considered as an ammeter. However, the readings of the

deflections on the scale of the instrument must be multiplied by a constant, the value of which depends upon the shunt used in order to obtain the true current values.

16. In Fig. 11 are shown the connections of a millivoltmeter and an external shunt of three ranges. One set of terminals connects the line to the shunt, and another set, the shunt to the millivoltmeter. The range of the instrument,

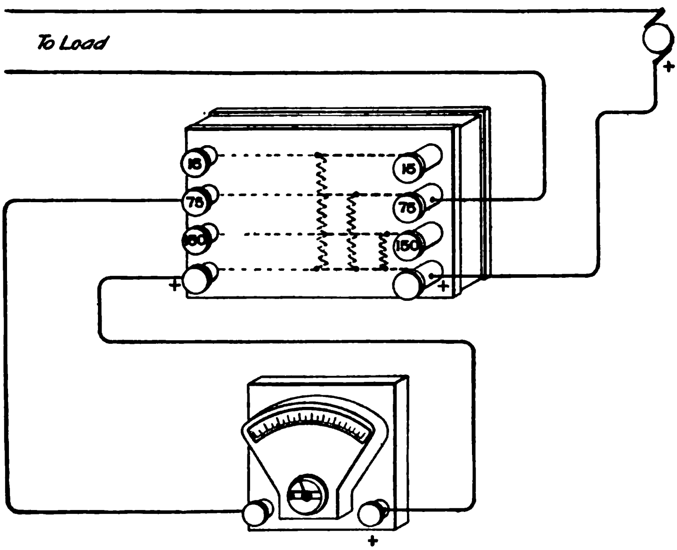


FIG. 11

as connected, is from 0 to 75 amperes. If the scale on the instrument is laid out so as to be direct reading for a full deflection of 15 amperes, the reading in this case must be multiplied by five in order to obtain the true current values. With this shunt box and this millivoltmeter, the range of the currents that may be measured is from 0 to 15, 0 to 75, and 0 to 150 amperes. The constants are 1, 5, and 10.

VOLTMETERS

17. Single-Scale Voltmeters.—Voltmeters that are provided with a single scale intended for only one range of values usually have two binding posts for connecting the instrument across the circuit. In order to have the current through the coil in the right direction, the binding post marked + is connected to the positive line wire and the other binding post is connected to the negative line wire. A small push button switch is often provided in the portable instrument, so that the voltmeter circuit may be closed only when a measurement is being taken.

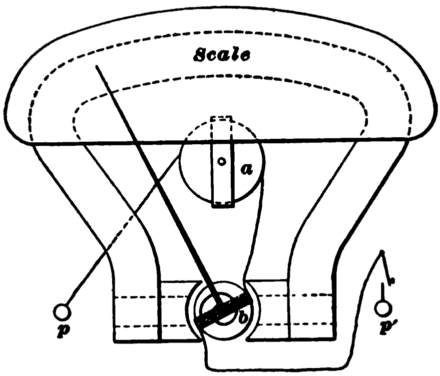


Fig. 12

Fig. 12 shows the working parts of a **Weston direct-current voltmeter** of the single-scale type. One end of resistance coil *a* is connected to the negative binding post *p* and the other, to the movable coil *b*. The other end of coil *b* is connected through a push button switch to the positive post *p'*.

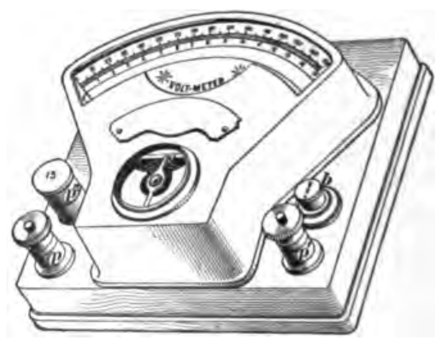


Fig. 13

18. Double-Scale Voltmeters.—In the case of voltmeters, the scale of which is intended to indicate two ranges of values, three binding posts are provided. The values of the upper scale are usually some even multiple of the values of the lower scale. Fig. 13 shows a double-scale voltmeter of maximum readings of 150

and 15 volts, binding posts p' and p being used with the 150-volt scale, and posts p' and p'' with the 15-volt scale. The post p' on the right is usually the positive terminal; both posts p and p'' are negative terminals.

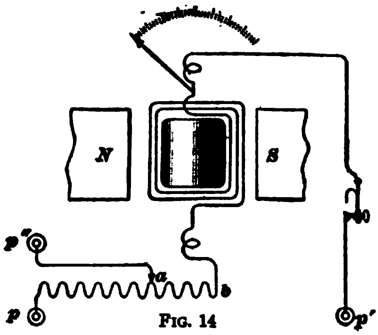


FIG. 14

19. The internal connections of a double-scale voltmeter are shown in Fig. 14. The resistance of the circuit from p' to p'' may be 15,000 ohms for use with the 15-volt scale and that of the circuit from p' to p may be 150,000 ohms for use with the 150-volt scale. The ratio between these resistances being 10, the voltage to cause a given current through the movable coil, and, therefore, a given deflection of the pointer, must be ten times as much when the connections for the large scale are used as when the connections for the small scale are used.

When using a double-scale voltmeter, care must be taken not to apply too high a voltage to the terminals p' and p'' of the lower resistance circuit. If these terminals are connected to a 125-volt circuit, the instrument may be burned out. The 150-volt terminals p' and p should be used for voltages greater than 15 and up to 150. If the voltage of a circuit is not known approximately, a test should be made with the high-reading scale first. Then, if the reading is less than the highest value of the lower reading scale, that scale should be used for a final test.

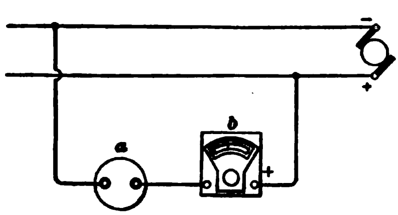


FIG. 15

20. Increasing the Range of a Voltmeter.—A voltmeter can be used to measure voltages much higher than its maximum scale reading by connecting a suitable resistor in series with the instrument across the circuit. Such a resistor

is called a *multiplier*. It is connected in the manner indicated in Fig. 15, in which the multiplier is shown at *a* and the voltmeter at *b*. Multipliers are made of such resistances that the scale reading must be multiplied by 2, 5, 10, 20, or 50 to obtain the voltage of the circuit that is under test.

ELECTRODYNAMOMETER INSTRUMENTS

21. In measuring instruments of the electrodynamometer type, the deflections are caused by the interaction of the magnetic fluxes of two or more coils, one of which is movable and is usually placed within a fixed coil or coils. Usually, there is no iron within the coils; therefore, the instruments have but little self-induction and many of them are suitable for either direct-current or alternating-current measurements of watts, volts, or amperes.

When measuring a direct current, readings are taken for both directions of current through the instrument. By this method, the influence of stray magnetic fluxes is eliminated, because if the stray flux acted in unison with the flux of the fixed coils during the first test it would act in opposition during the second test. The mean of the two readings, in such cases, is nearer to the correct value.

WATTMETERS

22. A **Weston indicating wattmeter** is shown in Fig. 16. This instrument is of the switchboard type and is designed for either direct-current or alternating-current measurements. The connections of this wattmeter to a circuit are indicated in Fig. 17.

The fixed coils *a*, Figs. 16 and 17, called the *series*, *current*, or *field coils*, are connected in series with the line wire of the circuit, or, in the case of large current values, to a shunt in the line wire. The magnetic flux produced by the current in the fixed field coils is therefore proportional to the current in the circuit.

The movable coil *b*, called the *potential coil*, is mounted on a shaft that is provided with steel pivot points supported

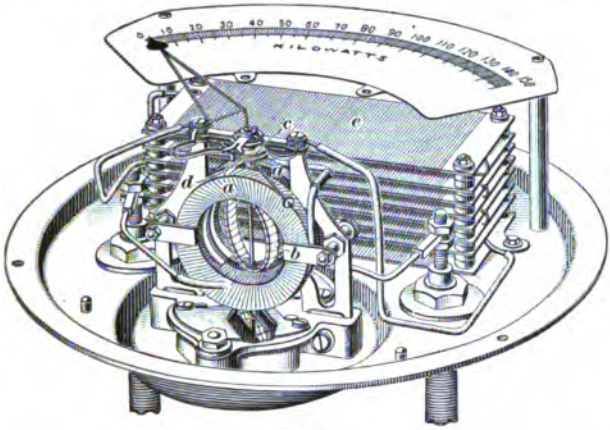


FIG. 16

in jewel bearings. Control springs *c* and *d* serve as conductors for current to and from the moving coil; they also keep the

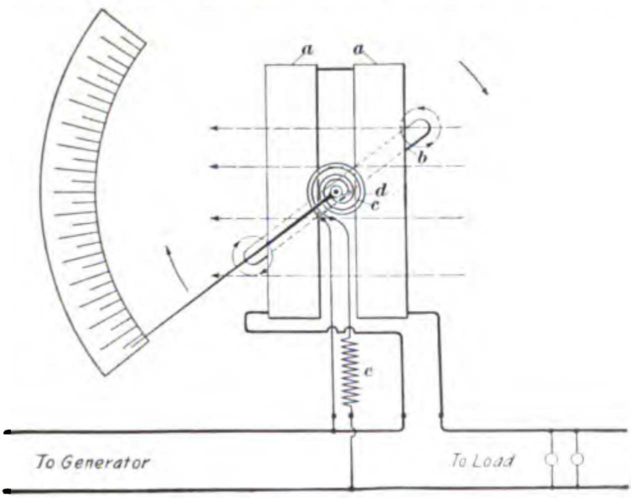


FIG. 17

pointer at zero when there is no current and oppose the movement of the coil when there is current. The movable coil

in series with a high non-inductive resistance *e* is connected across the circuit. The magnetic flux produced by the moving coil is therefore proportional to the difference of potential between the potential-coil terminals of the instrument.

23. The combined action of these two magnetic fluxes, one proportional to the current in the circuit and the other proportional to the voltage, tends to turn the movable coil toward a position in which its flux will coincide in direction with that of the flux of the fixed coils. The total turning effort is therefore proportional to the product of the instantaneous current and voltage, or to the watts. At the point of reading, the torque due to the magnetic action is balanced by the counter torque of the control springs, and the scale is so marked that the pointer indicates the watts corresponding to the load on the circuit.

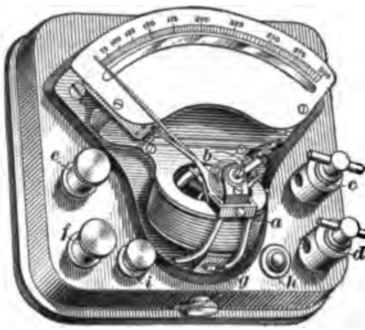


FIG. 18

More watts are required for the potential-coil circuit than for the series-coil circuit; therefore, in order that the instrument will not indicate these watts in addition to the circuit load, the potential coil is connected to the circuit on the generator side of the series-coil connections. The current in the potential coil does not, therefore, pass through the current coil.

24. The **Thomson inclined-coil wattmeter** is shown in Fig. 18. This indicating wattmeter operates on the same general principle as the inclined-coil instrument previously described. In this wattmeter, an inclined fixed coil *a* serves as the current coil and an inclined movable coil *b*, attached to the shaft of the moving element, serves as the potential coil. With current in both coils, the moving element tends to turn so as to make the two coil fluxes coincide in direction, and this movement is balanced by control springs. The extent of the movement is therefore proportional to the product

of the current in the two coils, or to the watts in the circuit, and the scale is marked to read watts.

The series-coil terminals of the Thomson wattmeter are shown at *c* and *d*, and the potential-coil circuit terminals at *e* and *f*. A device for clamping the moving system during transportation is operated by the button *g*. An air-damper vane is attached to the lower part of the pointer, and its action tends to make the instrument dead-beat. The button *h* operates a mechanical damper, which consists of a silk thread that can be brought into contact with the top of the pointer. The button *i* is used to complete the potential-coil circuit: the button may be locked in its closed position.

VOLTMETERS AND AMMETERS

25. Voltmeters and ammeters of the electrodynamometer type are constructed so as to be suitable for voltage and current measurements on either direct-current or alternating-current circuits. Their principle of operation is similar to that of the wattmeter. In the case of a voltmeter, the fixed coil, the movable coil, and a resistor are connected in series across the circuit. In the case of an ammeter for small currents, the fixed coil and the movable coil are connected in series, and the instrument is connected in series with one line wire of the circuit. For large currents, the movable coil of some ammeters is connected in parallel with the low-resistance series coil. This allows only a small current in the movable coil.

ELECTROSTATIC INSTRUMENTS

26. Electrostatic voltmeters and other measuring instruments of the electrostatic type, may be used on either direct-current or alternating-current circuits, but they are more commonly used to measure high alternating voltage.

The principle of their action is based on the mutual influence of adjacent charged bodies. Thus, if a fixed plate is connected to one side of a circuit and a movable plate, located near, but

not touching the first plate, is connected to the other side of the circuit, dissimilar charges will be impressed upon the plates, and these charges will attract each other. The movable plate, or vane, will move toward the fixed plate, and the extent of this movement indicates the voltage impressed on the instrument.

Electrostatic voltmeters take no current from a direct-current line while the voltage remains unchanged, and but a very small charging current from an alternating-current line. These voltmeters are better suited for high-voltage work, but instruments reading as low as 40 volts can be obtained.

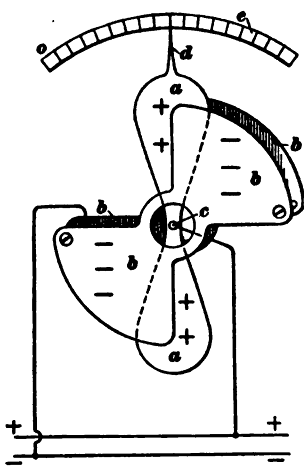


FIG. 19

27. Fig. 19 serves to illustrate the principle of an electrostatic voltmeter. In an instrument for direct-current service, several fixed and movable vanes are provided. The movable vane *a* is connected to the positive side of a direct-current circuit, and the fixed plates *b*, to the negative side. A positive charge is impressed on vane *a*, and a negative charge, on plates *b*. The attraction between these unlike charges draws the movable vane into the space between the fixed plates. The vane is so weighted below pivot *c* that when there is no voltage the pointer is at zero position.

When the instrument is active, the reading position is at the point of balance of the electrostatic forces and the force of gravity acting on the vane, and the latter force tends to return the vane to zero position. In some cases a small spiral spring serves as the controlling element. The pointer *d* indicates the voltage on the scale *e*.

Instruments intended for comparatively low direct voltages are provided with a large number of movable and fixed vanes in order to obtain large charging surfaces. The shaft

supporting the movable vanes is suspended by a wire; therefore, a very small turning effort will cause the movable vanes to enter the spaces between the fixed vanes.

HOT-WIRE INSTRUMENTS

THEORY OF ACTION

28. The action of **hot-wire instruments** is based on the heating effect of a current in a conductor and the change of length of the conductor with its change of temperature. The heat developed in a given conductor is proportional to the square of the current, and the length of the conductor varies directly with its temperature.

Fig. 20 illustrates the principle of hot-wire instruments. A wire is kept taut between two fixed points *a* and *b* by a spring *c*. A pointer attached to the wire at *d* moves over a scale marked so as to indicate the current or the voltage that is being measured. An increase of current in the wire causes the wire to lengthen; the spring takes up the slack, and the pointer moves along the scale toward the right. With a steady current, the pointer comes to rest at some point and a reading may be taken. If current decreases, the wire contracts and the pointer is moved toward the left to a new position. Commercial instruments are so arranged that a slight change in length of the conductor causes a considerable change in the position of the pointer.

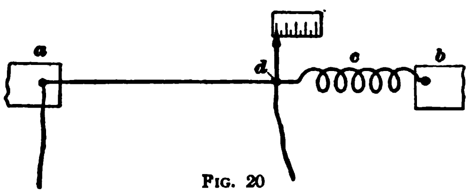


FIG. 20

COMMERCIAL FORMS OF INSTRUMENT

29. Instruments of the hot-wire type are made for measuring current or voltage on either direct-current or alternating-current circuits. An external shunt is employed with a

switchboard ammeter having a capacity greater than 5 amperes and an internal resistance for voltmeters reading up to 150 volts.

30. Principle of Operation.—Fig. 21 shows the exterior of a hot-wire switchboard ammeter, and Fig. 22, the working parts. The parts in both illustrations are indicated by the same reference letters. Current in the wire *a b*, Fig. 22, heats it and causes it to expand. To eliminate errors due to changes in room temperature, the wire is supported on a base that expands or contracts at the same rate as the wire when both are subjected to room temperature only. At a point on the wire *a b* is attached a second wire *c*. The other end of this wire *c* is fixed to post *g*. To this second wire is attached a very fine wire *d* that passes around a small pulley *e* and is held taut by a flat spring *f*. The pulley is mounted on a vertical shaft that also carries the pointer *h* and the aluminum damping disk *s*. The shaft is mounted on jewel bearings, so as to turn with the minimum amount of friction.

FIG. 21

The wire *a b* is stretched taut when not heated, and a very small expansion causes a considerable sag. The spring *f* takes up the sag in wires *a b* and *c*, and, since wire *d* is wound on pulley *e*, any increase or decrease of sag causes a movement of the pointer. The pointer moves to a position on the scale corresponding to the current measured. The dotted lines show in an exaggerated way the stretched positions of wires *a b* and *c*.

31. Adjustment and Damping.—The knob *n*, Fig. 21, serves to adjust the pointer at the zero point by slightly varying

the position of the post *a*, Fig. 22. The movements of the needle are damped by means of the aluminum disk *s*, Figs. 21 and 22, a portion of which turns between the poles of the permanent magnet *m*, Fig. 21, thus making the instrument dead-beat. The handle near the bottom of the case, Fig. 21, operates a switch so that the instrument circuit can be opened when no readings are desired.

32. Arrangement for Large Currents.—When the instrument is used to measure very small currents, the full

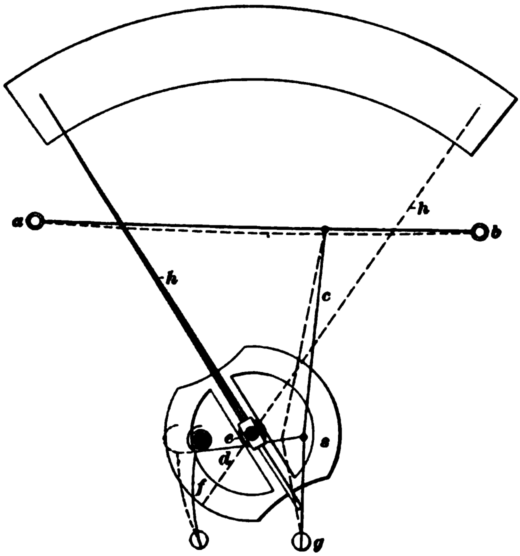


FIG. 22

length of wire *a b*, Fig. 22, carries the entire current that is to be measured. When used for measuring larger currents, however, the wire *a b* is tapped at one or more points by means of flexible silver strips, one of which is shown just below the scale in Fig. 21, and the sections of the wire thus formed are connected in parallel in order that the instrument will have greater current-carrying capacity.

When still larger currents are to be measured, a shunt of the type shown in Fig. 23 is employed. This shunt consists

of low-resistance strips *a* connected to heavy terminals *b*. The shunt is connected in the main circuit, and the ammeter is connected across the shunt by means of flexible cables furnished with the instrument. The cables are attached at

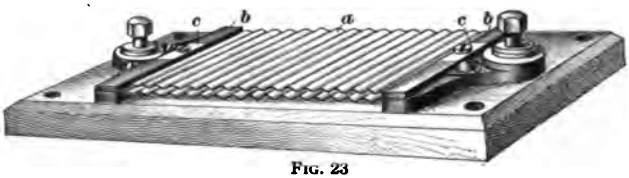


Fig. 23

points *c*, and it is important to see that the number on the cables corresponds to the number on the instrument; otherwise, the indications will not be correct. The internal resistance of the ammeter is very low, so that a small drop in voltage across the shunt is sufficient to operate the instrument.

RECORDING INSTRUMENTS

GENERAL PRINCIPLES AND CLASSIFICATION

33. A **recording instrument** is substantially an indicating instrument with a pointer arranged to trace a line on a paper chart that moves under the pointer at a uniform rate. The chart is marked with two sets of lines, one to represent time and the other to represent amperes, volts, watts, or whatever values the instrument may be designed to record. The line traced by the instrument shows the variation of the recorded values. Such instruments are very useful in power stations to record the variations of the station load.

Recording instruments may be classified as *direct-acting* and *relay*. In the direct-acting instruments, the moving element of the meter makes the record directly on the chart, and in the relay instruments, the moving element operates relay contacts that, in turn, cause a marking device to make the record on the chart.

In some recording instruments, the marking device at the end of the pointer is supplied with ink, and it draws either

a continuous or a dotted line on the moving chart. In other instruments, the sharp end of the pointer causes a series of dots to be made on the smoked surface of the chart.

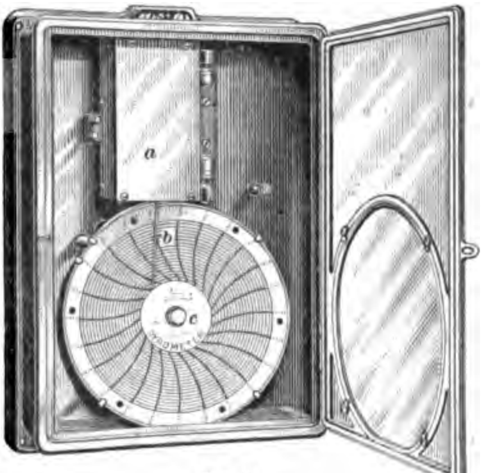


FIG. 24

DIRECT-ACTING RECORDER

34. A **Bristol recorder** with a chart in position is shown in Fig. 24. The measuring instrument, enclosed in a case, is shown at *a*; its pointer, at *b*; and a chart with a smoked surface, at *c*.

In Fig. 25 is shown the same recorder with the chart removed; also, the measuring instrument and its case are swung to the right so that the pointer will not interfere with the removal of the chart. Enclosed in the box *d* is a clockwork mechanism that turns the chart and also moves the arm *e* outwards intermittently. This arm forces the smoked surface of the chart against the end of the pointer. The pressure on the chart is applied for only a very small interval of time, however. During the intervening time, the pointer is free from contact with the chart. The line

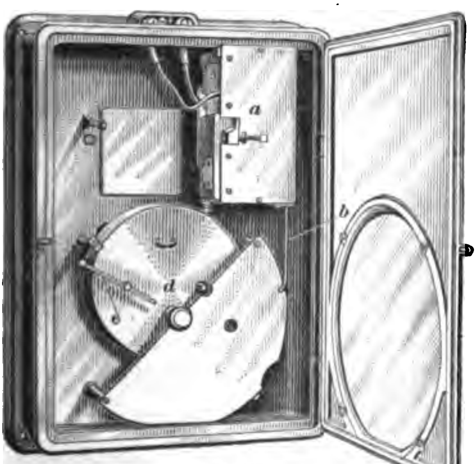


FIG. 25

of dots thus formed indicate the values of the quantity measured at very close intervals of time. When the chart is taken from the recorder case, it is dipped into a fixative solution, in order to make the tracing on the smoked surface permanent.

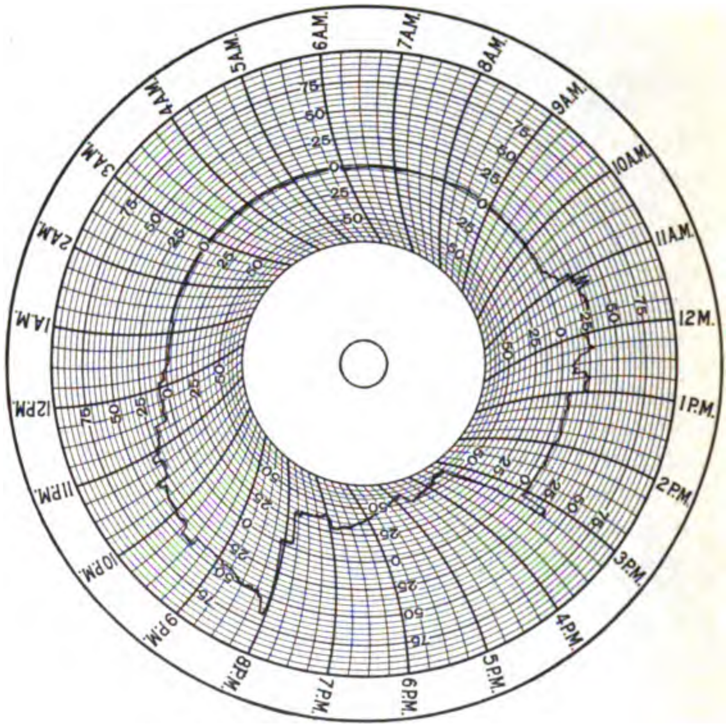


FIG. 26

The 24-hour record of an ammeter chart is illustrated in Fig. 26. It shows no current from 12:15 A. M. to 10:30 A. M. The current is in one direction from 10:30 A. M. to 3:15 P. M.; in the opposite direction from 3:15 P. M. to 8 P. M.; and in the original direction from 8 P. M. to 12:15 A. M.

RELAY RECORDER

35. In Fig. 27 is shown a graphic voltmeter of the relay type that is designed for either direct-current or alternating-current service and arranged to be mounted on a switchboard. The instrument contains two elements, a meter element and

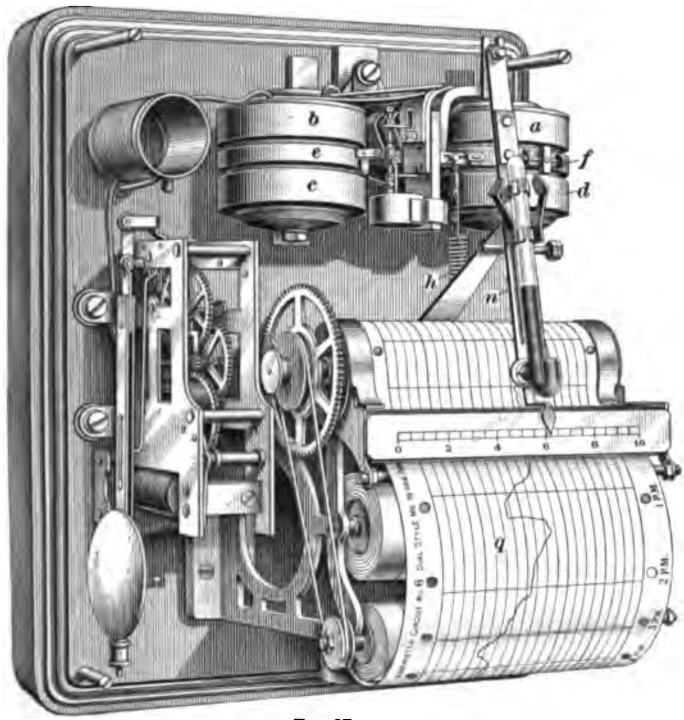


FIG. 27

a relay element. Fig. 28 shows a diagram of connections. Corresponding parts in both of these illustrations have the same reference letters.

36. The *meter element* consists of fixed coils *a*, *b*, *c*, and *d* and movable coils *e* and *f*. The movable coils are mounted on a beam that is pivoted at the center so as to tilt easily. All the coils and a resistor *g* are connected in series across the circuit. Current in the coils sets up fluxes that tend to move

coil *e* toward coil *c* and coil *f* toward coil *a*. The torque due to the magnetic forces is opposed by the action of a spring *h* connected between the balance arm and a part of the pen-moving mechanism. A contact arm *i* attached to the beam

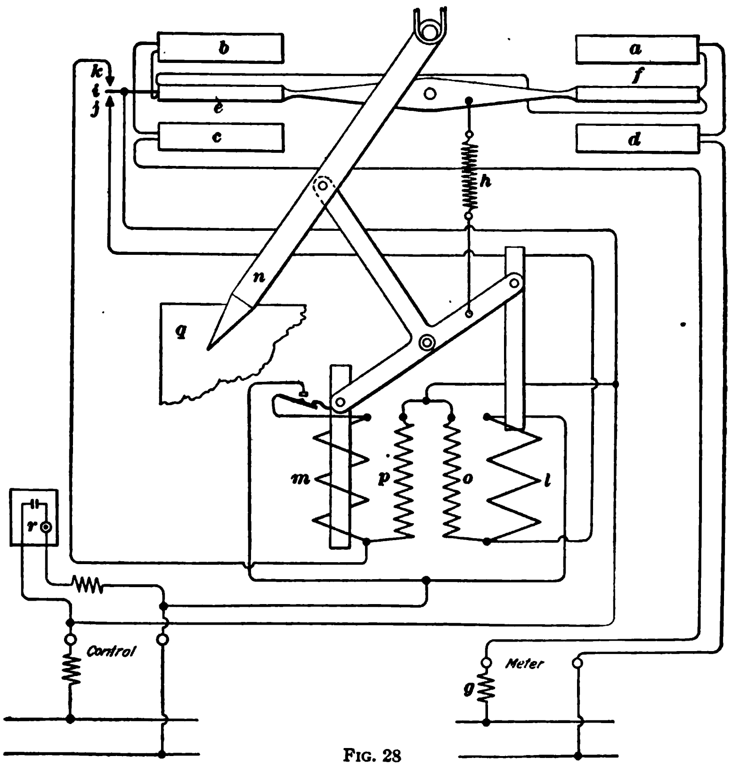


FIG. 28

makes connection with a contact point *j* when coil *e* moves downwards, and with point *k* when coil *e* moves upwards.

37. The *relay elements* consist of two coils *l* and *m* that are supplied with current from a separate control circuit. The movable cores of these coils are connected to the pen-moving levers, and the positions of these cores determine the position of the pen. When the instrument is active and the balance arm is in its center position, coil *l* is in series with resistor *o*

and coil *m* is in series with resistor *p*. The coils tend to draw their cores downwards, but as the magnetic forces of both coils are now small and balance each other, the pen remains at rest.

When the voltage increases, the current through the coils of the meter element increases, and the balance arm contact *i* makes connection with *j* and short-circuits resistor *o*. The current in coil *l* is thereby increased and its core is drawn down, turning the lever on its pivot and moving the pen arm *n* to the right. This movement puts spring *h* under greater tension and causes the balance arm to assume its central position, thus cutting the resistor *o* again into circuit with *l* and stopping further movement of the pen until the voltage again changes.

When the voltage decreases, the current through the coils of the meter element is decreased, and the spring *h* forces the balance arm to move so that contact *i* makes connection with *k*. Resistor *p* is now short circuited, thus increasing the current in coil *m*, and the pen arm moves to the left. This movement decreases the tension of spring *h*, the balance arm assumes its central position, and the pen arm stays in position until the voltage changes. The pen changes its position only when the voltage changes.

38. At zero position of the relay element, the circuit through coil *m* is opened by the cut-out shown near it. In this position, a projection at the end of the pen lever holds the cut-out open. The current otherwise taken from the control circuit for coil *m* and its resistor *p* is saved. The circuit through coil *l* and resistor *o* is complete, but, with resistor *o* in series, the current in coil *l* is too small to move the pen lever. Coil *l* is the first of the relay coils that becomes active when voltage is impressed on the metered circuit.

The pen is provided with an ink reservoir, and use may be made of a roll of paper that is long enough to record the variations in voltage during several weeks. The paper chart *q* is moved by a mechanism operated by a spring. The spring is rewound by a small motor *r* connected with the control circuit, and the motor is started and stopped automatically by the clock mechanism.

SPECIAL FORMS AND APPLICATIONS OF INSTRUMENTS

DIRECT-READING OHMMETER

39. Description.—The **Weston portable ohmmeter** is an instrument of the D'Arsonval type. In general construction, it is similar to a standard portable voltmeter, but it is provided with a scale reading in ohms instead of in volts. A small storage battery or some other source of constant electromotive force is used with the ohmmeter to supply the current for taking measurements. This type of ohmmeter is used for general resistance measurements ranging from 1 to 1,000 ohms, and it is particularly useful for the resistance measurements of incandescent-lamp filaments.

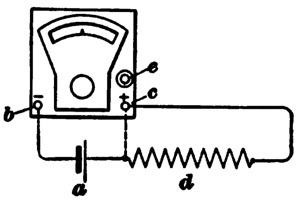


FIG. 29

40. Operation.—When a storage battery *a*, Fig. 29, having the electromotive force for which the Weston ohmmeter is designed is connected directly to terminals *b* and *c*, as indicated by the full and dotted lines, no external resistance being in circuit except the resistance of the battery, the current is sufficient to move the pointer from its no-current position at the extreme left to position *a* at *0* on the lower scale, Fig. 30.

If an external resistance *d*, Fig. 29, is added to the circuit, the current is decreased and the pointer, Fig. 30, takes up a position to the left of *0*. If *d*, Fig. 29, has a resistance of 10 ohms, the pointer rests at position *b*, Fig. 30, and the reading is 10 ohms.

If a resistance of from 50 to 100 ohms is to be measured, the key *e*, Fig. 29, is pressed so as to cut out 50 ohms of the

internal resistance of the instrument. If the resistance were just 50 ohms, the pointer would rest at *0*, Fig. 30, on the lower scale, which is the same as 50 on the upper scale. The total resistance of the internal and the external circuit is now the same as the total resistance of the battery and the internal circuit when *e*, Fig. 29, is not pressed and resistance *d* is not in circuit. If the resistance were more than 50 ohms, the pointer would take a position to the left of *0*, Fig. 30, and its value would then be read on the upper scale.

41. Correction-Factor Scale.—In some ohmmeters a correction-factor scale is provided for use when the electromotive force of the source does not cause the pointer to rest at *0*, Fig. 30, when only the source is connected to the ohmmeter. If the pointer rests at position *c* on the correction scale, the correction is + 1 per cent.; if it rests at *d*, the

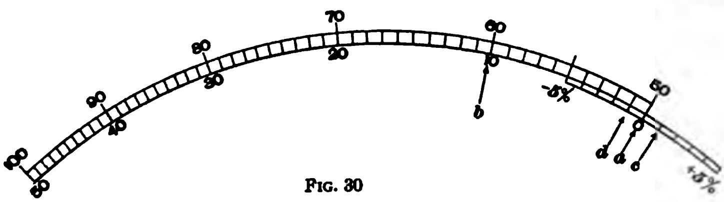


FIG. 30

factor is − 1 per cent. In order to apply the correction, the internal resistance of the instrument corresponding to the scale used must be known. This data is usually marked on the instrument base.

Let R = true resistance of the device;
R_1 = instrument reading;
p = correction factor, in per cent.;
r = internal resistance of the instrument corresponding to the scale used.

Then, $$R=R_1+p(R_1+r)$$

For example, if the test for the correction factor shows −4 per cent. and the resistance reading indicates 75 ohms, the internal resistance of the instrument then being 68 ohms, the true resistance is $R=75-.04\ (75+68)=69.3$ ohms, nearly.

When the lower scale of the instrument is in use the internal resistance is $68+50=118$ ohms. If the correction factor is then $+2$ per cent. and the resistance reading indicates 30 ohms, the true resistance is $R=30+.02\ (30+118)=33$ ohms, nearly.

ELECTRIC TACHOMETER

42. In Fig. 31 is shown a type of **portable electric tachometer** for measuring the speed of rotation of shafts. This device consists of a small direct-current magneto generator *a* and a voltmeter *b*, the scale of which is marked to read revolutions per minute. The generator shown has on its

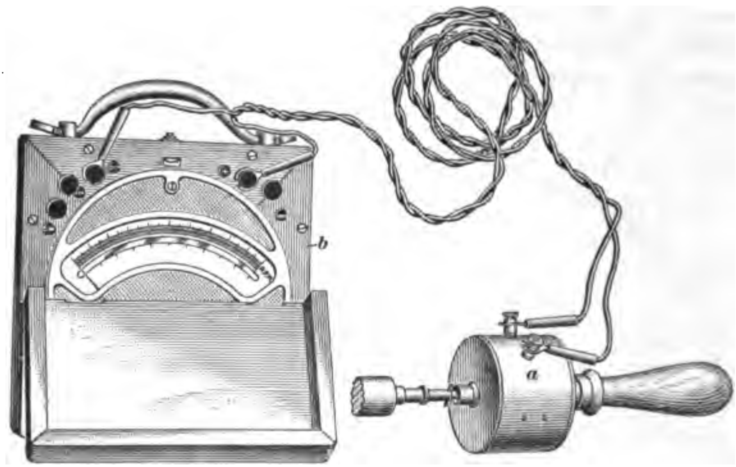


FIG. 31

shaft a diamond-shaped point that is held firmly against the end of a rotating shaft. The generator speed and the voltage are proportional to the speed of the shaft, and this speed is indicated by the voltmeter.

In *stationary tachometers*, the generators are belted or otherwise connected to the shaft, and the indicators can be mounted on the switchboard or at other convenient places.

To increase the range of readings, a double scale and a divided internal resistance are sometimes provided.

ELECTRIC PYROMETERS

43. Electric pyrometers, whether of the *thermoelectric-couple* or the *resistance* type, are used to indicate temperatures.

44. In the **thermoelectric-couple pyrometer,** the junction of two metals is thrust into the furnace or other source of heat to be measured. The electromotive force generated by the couple is impressed on a millivoltmeter, the scale of which is marked to read in degrees of temperature of the furnace. If the temperature of the furnace rises, the electro-

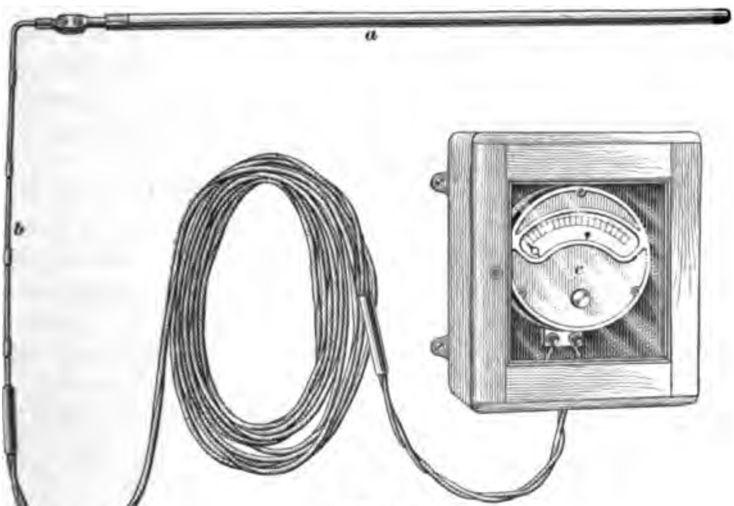


FIG. 32

motive force is increased and the instrument indicates a higher reading. A lower temperature is indicated by a lower reading.

Fig. 32 shows a pyrometer of this type. The couple is placed within the protecting tube *a*, and an extension piece *b* is connected to the cold ends of the couple. The extension piece of the couple is connected by flexible cable to the indicator *c*.

45. Changes in the room temperature affect the reading of such an instrument to some extent by changing the difference

of temperature between the *hot* and *cold* ends of the couple. If the room temperature is subject to change, a *compensator*, Fig. 33, is sometimes connected in the circuit, as indicated at *d*, Fig. 34, in which illustration the reference letters *a*, *b*, and *c* indicate the parts so lettered in Fig. 32. The compensator consists of a bulb of mercury into which extends a loop of fine platinum wire that forms a part of the circuit. If the room temperature rises so as to reduce the difference of temperature between the ends of the couple, the mercury rises and short-circuits more of the platinum loop, thus proportionally reducing the resistance in series with the instrument, keeping the current at practically a constant value for a given furnace temperature, and compensating for the change in the room temperature.

FIG. 33

46. The operation of **resistance pyrometers** is based on the change of resistance in a wire caused by a change in temperature of the wire. A piece of wire, either of platinum or nickel, is placed in a tube that is thrust into the furnace. The changes in the resistance of the wire, due to changes in temperature of the furnace, are indicated in some pyrometers by means of a form of Wheatstone bridge; in others, these changes are indicated by a measuring instrument having two movable coils, current through one being practically steady and current through the other being varied by any change in the resistance of the tube wire. The position of the moving element of the instrument, which indicates degrees of temperature, is changed if the current in one of the coils is varied.

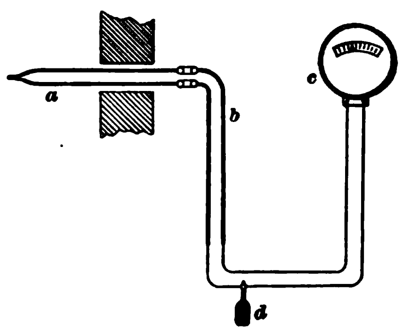


FIG. 34

USE OF INSTRUMENTS FOR MEASUREMENTS

MEASUREMENTS WITH AMMETERS AND VOLTMETERS

47. Measurements of Current, Difference of Potential, and Resistance.—In Fig. 35 is shown a battery *a*, a coil *b*, an ammeter *c*, and a voltmeter *d*. It is desired to find the current in the coil, the voltage impressed on it, and its resistance. The ammeter is connected in series with the coil, so that all the current passing through the coil must pass through the ammeter also. The reading of the ammeter indicates the current. The voltmeter is connected across the terminals of the coil, and its reading indicates the difference of potential, expressed in volts, that is impressed on the coil. The resistance of the coil, expressed in ohms, as determined by Ohm's law, is

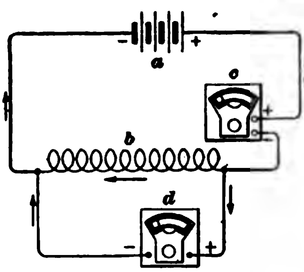


Fig. 35

$$R = \frac{E}{I},$$

in which R = resistance;
E = voltmeter reading;
I = ammeter reading.

For example, if $E = 6$ volts and $I = 1.2$ amperes, the resistance of the coil is 5 ohms.

The ammeter as connected measures the current that passes through the coil and voltmeter in parallel; but the voltmeter resistance is usually so high that the effect of the current in the voltmeter circuit may be neglected. The ammeter connecting wires should be short and of low resistance; the voltmeter connecting wires may be longer and of higher resistance

The resistance of the voltmeter leads is very small compared with the high internal resistance of the instrument.

48. High and Low Resistances.—Ammeters and voltmeters may be employed in the manner just explained to measure a wide range of resistances. When the resistance is high, a low-reading ammeter and a comparatively high-reading voltmeter should be used. When the resistance is low, a high-reading ammeter and a low-reading voltmeter should be used.

This method, sometimes known as the *fall-of-potential method,* is useful in determining the resistance of armatures, of starting resistance sections, and of poor joints between conductors, such as poor contacts on a switch, etc. The voltmeter or millivoltmeter terminals should be applied directly to the terminals of the device under test, and the current should be high enough to obtain readable deflections.

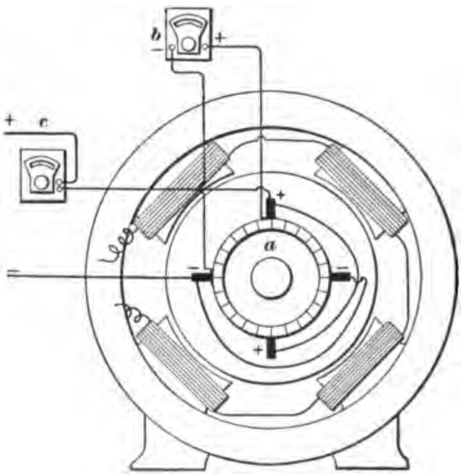


Fig. 36

49. Armature Resistance.—In Fig. 36 is shown the application of the preceding method to a resistance test on an armature *a* of a generator or a motor. The field circuit of the machine is opened so that the armature will not rotate during the test. The terminals of a millivoltmeter *b* are placed under brushes of opposite polarity, and a small current is established in the armature. An ammeter *c* in the armature circuit indicates the value of this current, and a rheostat (not shown) can be used to keep the current within safe limits and to obtain readable deflections.

Several readings should be made with the armature in different positions, and the mean of the readings taken. The

millivoltmeter reading divided by the ammeter reading gives the resistance of the armature. This includes the joint resistance of the parallel paths through the armature windings and the commutator, but not the resistance of the brushes.

MEASUREMENTS WITH A VOLTMETER

50. Measurement of Current With a Voltmeter. The current in a simple circuit can be determined by means of a voltmeter and a known resistance. The high-resistance voltmeter *a*, Fig. 37, is connected across the terminals of the known resistance *b*, through which a current passes from a source of electromotive force *c*. The current through the circuit is

$$I = \frac{E}{R},$$

in which, I = current through circuit;
E = reading of voltmeter a;
R = known resistance of b.

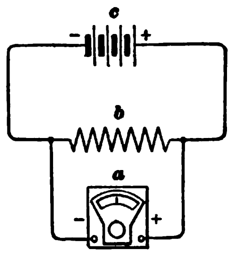


FIG. 37

51. Measurement of Resistance With a Voltmeter. A resistance *a*, Fig. 38, can be measured by means of another resistance *b* of known value and a high-resistance voltmeter *c*. The voltmeter *c* is first connected to the terminals of the unknown resistance *a* and then to the terminals of the known resistance *b*. These resistances are connected in series; therefore, the same current passes through them from the source *d*.

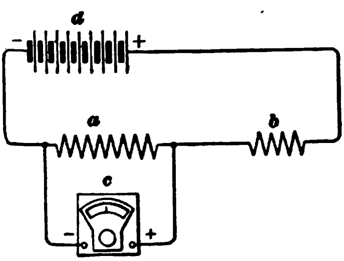


FIG. 38

The resistances of coils *a* and *b* are proportional to the readings of the voltmeters when connected to the terminals of the coils.

Let R = unknown resistance a;
R_1 = known resistance b;
E = volts drop through a;
E_1 = volts drop through b.

Then, $$R : R_1 = E : E_1$$

and $$R = \frac{R_1\ E}{E_1}$$

For example, if the drop in volts E through a is 3.69 volts, the drop E_1 through b 2.6 volts, and the resistance R_1 of b .26 ohm, the resistance of a is

$$R = \frac{.26 \times 3.69}{2.6} = .369 \text{ ohm}$$

52. Measurement of Insulation Resistance of Line Wires With a Voltmeter.—The insulation resistance between either line wire of a two-wire circuit and the ground may be determined roughly by means of a voltmeter. The connections for one test of this kind is indicated in Fig. 39. The voltmeter a is first connected across the circuit, the leads being in positions b and c. The voltmeter is then connected between the negative line wire and the ground, the leads then being at positions c and d. Another connection of the voltmeter is between the positive line wire and the ground, the leads then being in positions b and e. There may be a number of leakage paths from either line wire to the ground. These groups of paths are indicated by f and g. The faults on the line wires and the voltmeter form paths from one side of the circuit to the other side when the voltmeter has one terminal grounded. The readings should be taken as quickly as possible and the voltage of the line should be steady. A good ground connection is made by touching the voltmeter lead to a water pipe or other metal structure that is in contact with the earth.

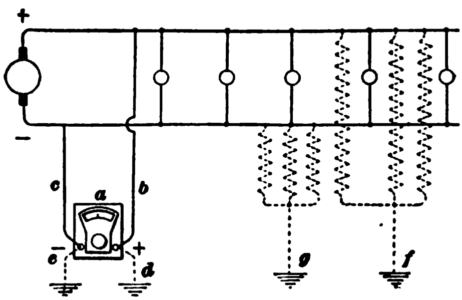


Fig. 39

Let e = reading for first test;
e_1 = reading for second test;
e_2 = reading for third test;
R = insulation resistance between positive line wire and ground;
R_1 = insulation resistance between negative line wire and ground;
r = internal resistance of voltmeter.

Then,
$$R=r\left(\frac{e}{e_1}-1\right) \qquad (1)$$
$$R_1=r\left(\frac{e}{e_2}-1\right) \qquad (2)$$

EXAMPLE.—When determining the insulation resistance between the two line wires of a circuit and the ground with a voltmeter having an internal resistance of 12,200 ohms, the voltage e between line wires is found to be 113; the voltage e_1 between the negative line wire and the ground, 4; and the voltage e_2 between the positive line and the ground, 1. What is the insulation resistance of: (*a*) the positive line wire? (*b*) the negative line wire?

SOLUTION.—(*a*) The insulation resistance between the positive line wire and the ground is, according to formula **1**,
$$R=12{,}200\left(\frac{113}{4}-1\right)=332{,}450 \text{ ohms. Ans.}$$

(*b*) The insulation resistance between the negative line wire and the ground, is according to formula **2**,
$$R_1=12{,}200\left(\frac{113}{1}-1\right)=1{,}366{,}400 \text{ ohms. Ans.}$$

53. Measurement of Insulation Resistance of a Generator With a Voltmeter.—The insulation resistance of the windings of a generator may be measured with approximate accuracy by the method just described for line wires. The positive terminal of the voltmeter is connected to the positive terminal of the generator (while running), and the other voltmeter terminal is touched to the frame of the machine. If the pointer is not deflected appreciably, the insulation resistance is fairly high. A similar test should be made with the voltmeter connected between the negative generator

terminal and the frame. The line circuit should be disconnected while making the test.

Formula 1, Art. 52, should be used in case the insulation resistance is to be calculated. The voltage of the circuit is e, and the voltage between one generator terminal and the frame is e_1.

MEASUREMENT OF POWER

54. Measurement by Voltmeter and Ammeter.—The power, in watts, of a direct-current circuit can be determined by finding the product of the volts across the circuit and the amperes in it.

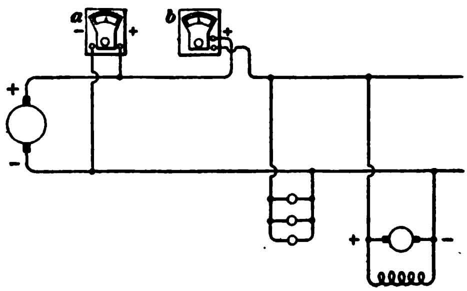


FIG. 40

The connections for any circuit or branch circuit are shown in Fig. 40. The voltmeter a across the circuit indicates the volts, and the ammeter b in series with the circuit indicates the amperes. The product of the two readings is the power, in watts.

55. Measurement by Wattmeter.—In Fig. 41 are shown the connections of a wattmeter a to measure the power of the main circuit at the generator. The potential-coil terminals should be connected across the circuit on the generator side of the current-coil connections, which are in series with one line wire. The reading of the wattmeter indicates the power required for two branch circuits and the line losses.

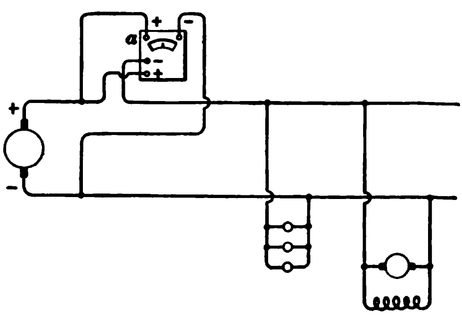


FIG. 41

CALIBRATION OF INSTRUMENTS

CALIBRATION BY COMPARISON OF SIMILAR INSTRUMENTS

56. The **calibration** of a measuring instrument from the operator's point of view, is the process of determining the error, provided there is one, of any of the indications of the pointer

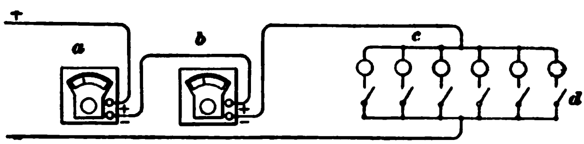


FIG. 42

on its scale. It is important that all electrical measuring instruments be accurate. Occasional comparison with other instruments known to be accurate is therefore advisable. Any errors in the indications can thereby be detected and corrections thereafter applied. Such comparison requires that the two instruments should be affected by the same values of the quantities measured.

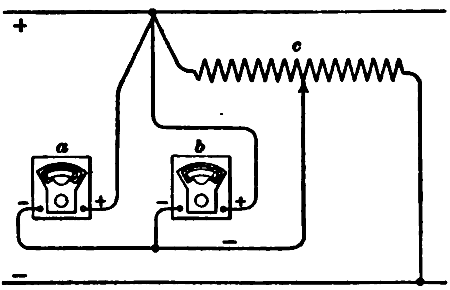


FIG. 43

57. Comparison of Ammeters.—Two ammeters can be compared by connecting them in series in a circuit in which the voltage is steady and the current can be varied. In Fig. 42 the ammeters are shown at *a* and *b* and a lamp bank at *c*; the current is varied by switching lamps off or on by small switches *d* and the ammeters are compared for several readings.

58. Comparison of Voltmeters.—In Fig. 43, the connections for a comparison test of two voltmeters *a* and *b* are shown. A high resistance *c* is connected across the circuit. Two corresponding terminals of the voltmeters are connected together and to one line wire. The two other terminals are connected together and touched to different points on the resistance *c*. The voltmeter should be compared for several different readings of voltages and any errors recorded.

59. Comparison of Wattmeters.—Two wattmeters are compared by connecting both so that they will measure

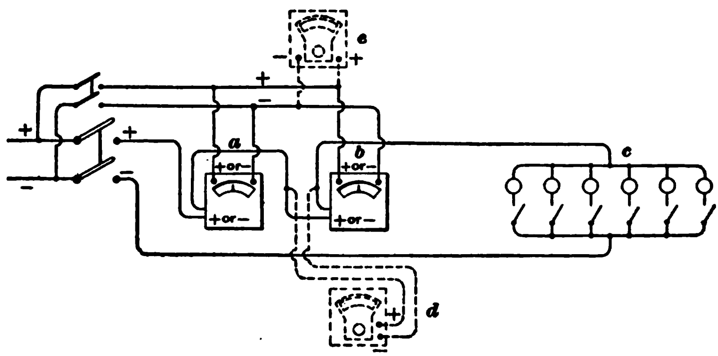


FIG. 44

the rate at which energy is expended in the same circuit and then varying the rate so as to make comparisons for several different points on the scales. Fig. 44 indicates the connections of the wattmeter *a* under test, the standard wattmeter *b*, and the lamp bank *c*. If the standard wattmeter *b* is not available, the test of a direct-current wattmeter can be made by means of an accurate ammeter *d* and a voltmeter *e*. The connections of the ammeter and voltmeter are shown by dotted lines. In this case the standard wattmeter *b* and its connections in Fig. 44 should not be considered.

CALIBRATION TABLES AND CURVES

60. If the calibration test on an instrument shows that the readings are seriously inaccurate, it is usually best to return the instrument to the manufacturer for repair and adjustment.

A table may be prepared showing in one column the readings of the instrument under test, in the next column the

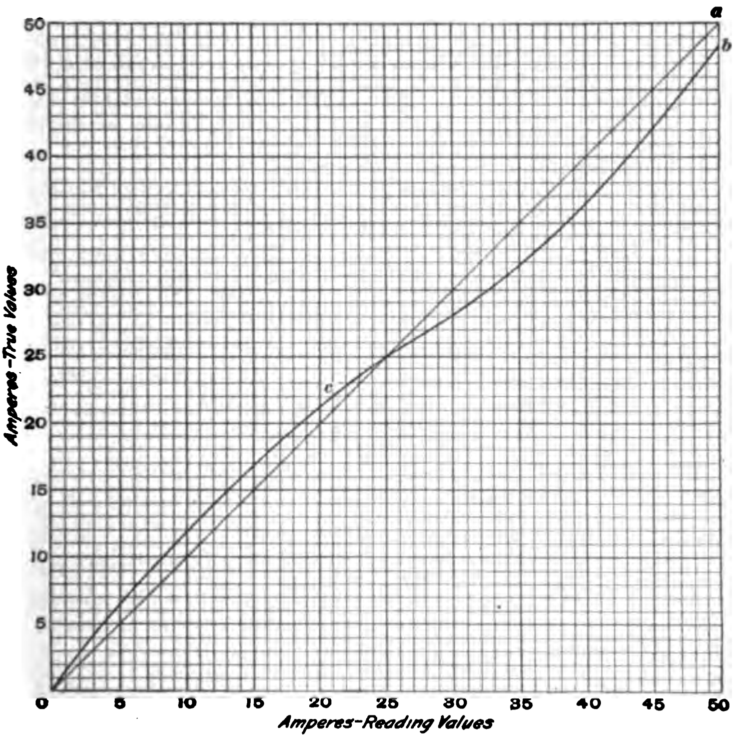


FIG. 45

readings of the standard instrument, and in the last column the corresponding per cent. error of the scale or the actual number of units that the scale is in error. The table should be kept near the instrument for convenient reference.

61. A calibration curve such as that shown in Fig. 45 can be constructed to take the place of the table. The true values

are shown in the vertical data line and the readings of the instrument under test in the horizontal data line. If the instrument had been correct, the straight line *0–a* would represent the. calibration line. In this case, however, the instrument was not correct and the curved line *0–b* indicates the calibration line. The points on this curve are determined by the intersection of a vertical line through a reading value with a horizontal line through the true value corresponding to that reading value. For example, if the ammeter reading is 21 amperes and the standard, or true, value is 22 amperes, the intersection of the vertical and horizontal lines is at *c*. This forms a point on the curve. Other points can be located and curve *0–b* constructed.

After the curve has been drawn, any true value may be found from any reading value by tracing vertically from the reading value to curve *0–b* and then horizontally to the true value. The vertical distance between any point on the straight line and the curve represents the units that the scale of the instrument is in error at that point. In the case shown, the first part of the scale reads too low and the last part too high. At point *c* the reading is 1 ampere too low.

ALTERNATING CURRENTS
(PART 1)

GENERAL THEORY

REPRESENTATION AND DEFINITIONS

VARIATIONS OF ALTERNATING ELECTROMOTIVE FORCE

1. When a conductor is moved in a magnetic field so as to cut lines of force, electromotive force is induced in the conductor. If the direction of motion and the direction of the lines of force remain unchanged, the direction of the electromotive force is uniform; and if the conductor forms part of a closed circuit, direct current exists in the circuit. But if the direction of the lines of force periodically reverses while the conductor moves across them, as in moving the conductor past alternate north and south magnetic poles, *alternating electromotive force* is induced in the conductor, and **alternating current** is established in a closed circuit of which the conductor forms a part.

2. In practically every dynamo-electric machine, alternating voltage is induced in the armature conductors, because the direction of the lines of force reverses at each pole. In direct-current generators the commutator changes the alternating current in the armature conductors to direct current for the external circuit, while in alternating-current generators, or *alternators*, the current in the external circuit is the same as that in the armature conductors, both alternating.

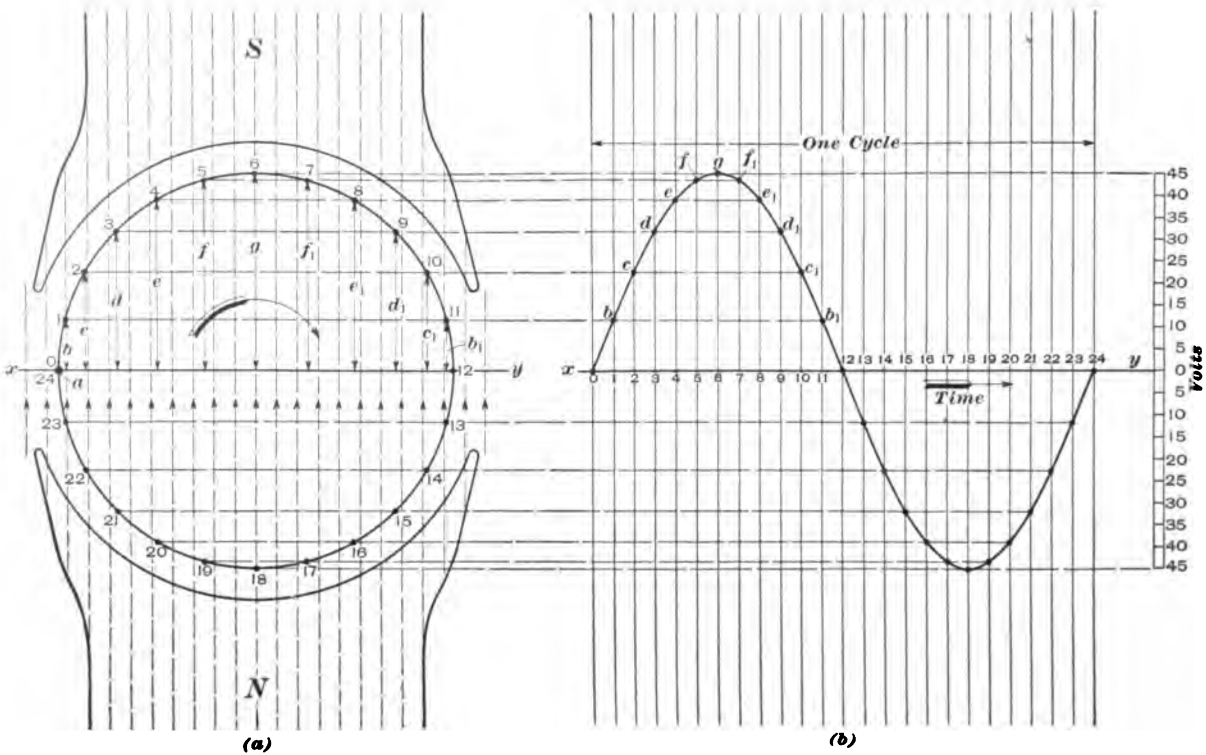


FIG. 1

3. The value of an electromotive force set up in a conductor that cuts lines of force is at every instant directly proportional to the rate of cutting the lines; that is, to the number of lines cut per unit of time.

Fig. 1 (*a*) represents an end of a round iron drum carrying one conductor *a* and assumed to be rotating at a uniform speed in a uniform magnetic field; the rotation is clockwise, as indicated by the curved arrow, and the lines of force, represented by the broken lines, are in the direction indicated by the arrowheads immediately below the line *x y*. At the instant of passing through point *0*, midway between the poles, the conductor moves parallel to the lines of force, and does not cut them; therefore, no electromotive force is generated in the conductor. As the conductor moves on through points *1*, *2*, *3*, etc., the rate of cutting the lines increases until at point *6* the conductor moves at right angles to the lines, cutting them at the most rapid rate; therefore, the highest electromotive force is set up in the conductor.

Further movement through points *7*, *8*, *9*, etc., will cause a gradual reduction in the rate of cutting the lines and in generated electromotive force, until again, at point *12*, no lines are cut and no electromotive force is set up. As the movement continues through points *13*, *14*, etc., the rate of cutting the lines of force increases, and the electromotive force becomes a maximum at point *18*, after which it again decreases to zero at point *24*, which is identical with the starting point *0*.

The motion of the conductor relative to the direction of the lines reverses at the end of each half revolution, being from left to right in the first half and from right to left in the second half, looking in the direction of the lines of force. The generated electromotive force therefore reverses at the end of each half revolution, and if the conductor continues to revolve an alternating electromotive force is set up in it.

4. Assume that the conductor moves at a uniform rate around the circle, and that the density of the lines of force is uniform through all parts of a cross-section *x y* midway between the poles. The rate of motion can be represented by abscissas,

or distances, *0 – 1*, *1 – 2*, etc. along the axis $x\,y$, Fig. 1 (*b*), and the electromotive force induced while moving through each of these distances, by the ordinates *1 – b*, *2 – c*, *3 – d*, etc., equal to the vertical distances *b*, *c*, *d*, etc. in (*a*). A line drawn through the points *b*, *c*, *d*, etc., Fig. 1 (*b*), has the wavelike form shown.

The induced electromotive force is in one direction in the conductor while passing one pole, as from point *0* to point *12*, Fig. 1 (*a*), and in the other direction while passing the other pole. The first half of the curve in (*b*) is therefore shown above the axis $x\,y$ and is called *positive*; the second half *12 – 24* is shown below the axis and is called *negative*. Assuming that in this particular conductor the maximum electromotive force is 45 volts, instantaneous value at any point during the revolution can be read off the scale at the extreme right of (*b*) by laying a straightedge against the point and parallel to the axis and noting where it crosses the scale.

5. The curve, Fig. 1 (*b*), is called a **sine curve.** The generated electromotive force, or the resulting current in any conductor on an armature that rotates at a uniform speed in a uniformly distributed magnetic flux, can always be represented by a sine curve. The electromotive forces generated in commercial alternators always deviate more or less from a true sine form, owing to irregularities in the distribution of the magnetic flux. For automatically tracing a curve and thus showing successive instantaneous values of electromotive force or current, use is made of an instrument called the *oscillograph*. By means of this instrument, the exact wave form of any alternator can be found.

Calculations in alternating-current work are based on sine curves; the departure of the electromotive force or current from the true sine curve is usually not enough to affect such calculations for practical purposes.

CYCLE, FREQUENCY, AND ALTERNATION

6. A **cycle** is one complete set of the electromotive forces continually recurring in each conductor of an alternator. One cycle of changes occurs in each conductor while it is passing

the faces of one pair of poles, and these changes can be represented by a curve, as in Fig. 1 (*b*). In a two-pole machine, 1 cycle is completed per revolution; in a four-pole machine, 2 cycles per revolution; in a six-pole machine, 3 cycles per revolution; etc. If the speed of the armature is uniform, the time taken to pass each pair of poles, or for completing 1 cycle, is always the same. The word *period* is sometimes used with the same meaning as cycle.

7. The number of cycles per second is called the **frequency**. Since a two-pole machine completes 1 cycle per revolution, the number of cycles per second, or the frequency, is the same as the number of revolutions per second. A machine with more than two poles completes as many cycles per revolution as there are pairs of poles; hence, the number of cycles per second equals the number of pairs of poles multiplied by the number of revolutions per second.

Let f = frequency, in cycles per second;
r. p. m. = speed, in revolutions per minute;
n = number of pairs of poles.

Then,
$$f = \frac{\text{r. p. m.}}{60} \times n$$

Frequencies of 25 and 60 cycles are in general use, the first chiefly for power purposes and the second chiefly for lighting, although either of these frequencies can be used for power or lighting. Frequencies lower than 25 are used to some extent, mostly in alternating-current railway work, but they are unsatisfactory for lighting because they cause lights to flicker. In some localities, 30, 40, and 50 cycles are in use, and in some older stations intended for lighting only, frequencies as high as 133 are found.

EXAMPLE.—An alternator is driven at a speed of 375 revolutions per minute. What is the frequency of the system if the alternator has eight poles?

SOLUTION.—The number of pairs of poles is $8 \div 2 = 4$, and, according to the formula,

$$f = \frac{375}{60} \times 4 = 25 \text{ cycles per sec.} \quad \text{Ans.}$$

8. An **alternation** is half a cycle; it is therefore represented by one of two half waves representing a cycle. There are two alternations for every cycle. Instead of expressing the frequency of an alternator in cycles per second, it was formerly expressed in alternations per minute. Thus, a frequency of 60 cycles per second, or 3,600 cycles per minute, was expressed as 7,200 alternations per minute.

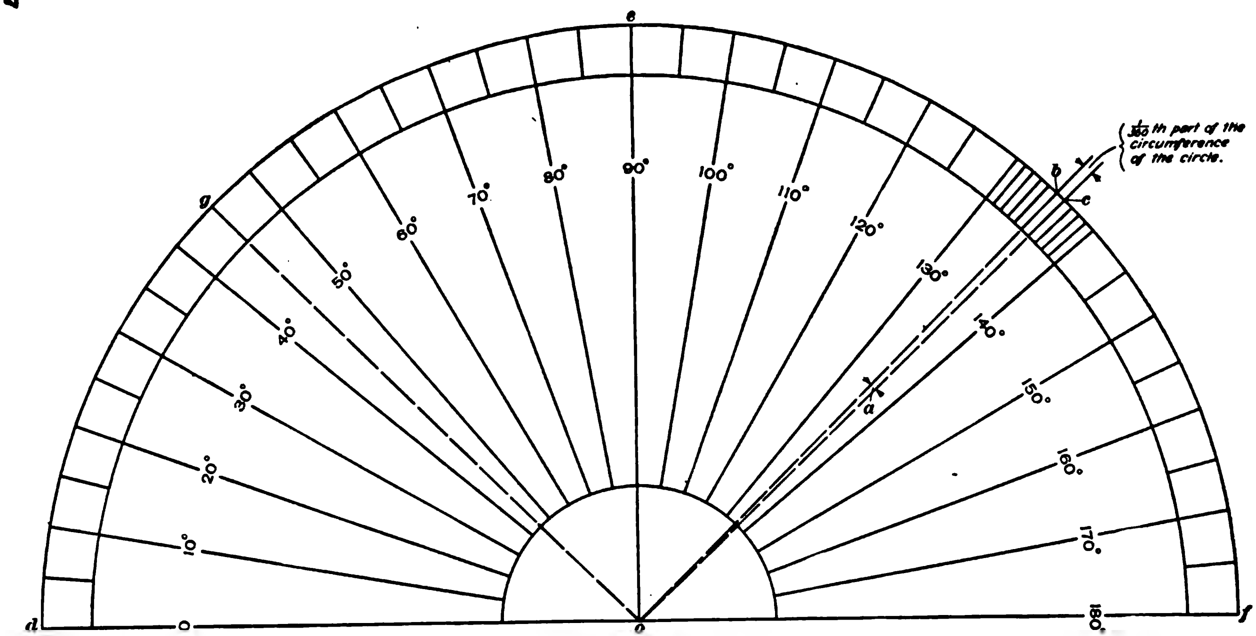
SPACE-DEGREES AND TIME-DEGREES

9. One of the 360 equal parts into which the circumference of a circle may be divided is an arc of one degree, written 1°; the angle between lines drawn from the extremities of this arc to the center of the circle is an angle of 1°. Fig. 2 shows a semicircle with some of the angular divisions indicated. The angle a between the two radial lines $o\,b$ and $o\,c$ is an angle of 1°, and the arc $b\,c$ is an arc of 1°. The arc $d\,e$ is an arc of 90°, and it is said to subtend an angle of 90°; that is, angle $d\,o\,e = 90°$, or one-fourth circle. Likewise, arc $d\,e\,f$ is an arc of 180°, subtending an angle of 180°, or one-half circle. These degrees may be called **mechanical space-degrees,** or simply *space-degrees*, when necessary to distinguish them from others used in electrical calculations.

10. The time taken to complete a cycle is arbitrarily assumed to consist of 360 intervals called **electrical time-degrees,** or simply *time-degrees*. To complete a cycle, the conductor must pass across the faces of two unlike poles, or through 360 time-degrees. In Fig. 1 (a) each division of the circular path of the conductor represents $\frac{1}{24}$ cycle, or $\frac{1}{24} \times 360 = 15$ time-degrees. The conductor is therefore in position *2* 30 time-degrees later than in position *0*, and so on.

In Fig. 1 (b), time is measured along the horizontal axis $x\,y$; therefore, the distance *0 – 24* represents 360 time-degrees and each division, *0 – 1*, *1 – 2*, etc., 15 time-degrees. The maximum value is reached 90 time-degrees after zero value, and the next zero value, 90 time-degrees after the maximum value.

There is always a difference of 90 time-degrees between the *maximum* and the *zero* value; also 180 time-degrees between the



e
g
d
o
f
a
b
c
0
10°
20°
30°
40°
50°
60°
70°
80°
90°
100°
110°
120°
130°
140°
150°
160°
170°
180°
$\frac{1}{360}$ th part of the circumference of the circle.

FIG. 2

maximum positive and the *maximum negative* value; or between two consecutive zero values.

The value of 1 time-degree, in seconds, depends on the frequency. When the frequency is 60, 1 cycle is completed in $\frac{1}{60}$ second. As there are 360 time-degrees per cycle, the value of 1 time-degree in this case is $\frac{1}{360} \times \frac{1}{60} = \frac{1}{21,600}$ second.

11. The movements of armature conductors are usually stated in **electrical space-degrees**, or simply *electrical degrees.*

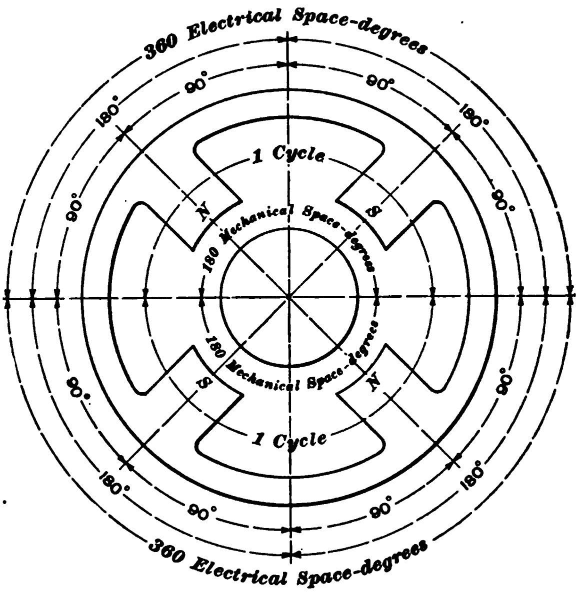


Fig. 3

The conductor moves through 1 electrical degree during 1 time-degree. Thus, during 1 cycle the conductor passes through 360 electrical degrees. In a two-pole machine, 1 electrical degree is equal to 1 mechanical space-degree, because the conductor has to move through 360 mechanical space-degrees in order to complete 1 cycle or 360 electrical degrees. In a four-pole machine, Fig. 3, 1 electrical degree is equal to ½ mechanical space-degree, because the conductor has to move through 180

mechanical space-degrees in order to complete 1 cycle, etc. In any case, 1 mechanical space-degree is equal to as many electrical degrees as there are pairs of poles.

EXAMPLES FOR PRACTICE

1. A two-pole turbo-alternator is supplying a 60-cycle system. What is the speed of the alternator in revolutions per minute?
Ans. 3,600 rev. per min.

2. A two-pole turbo-alternator is running at a speed of 1,500 revolutions per minute. What is the frequency of the system?
Ans. 25 cycles per sec.

3. What length of time, in seconds, corresponds to 45 electrical time-degrees on a 25-cycle system? Ans. $\frac{1}{200}$ sec.

4. In a six-pole alternator, how many mechanical space-degrees are equal to 90 electrical degrees? Ans. 30°

VALUES AND PHASE RELATIONS

12. Values Used in Practice.—The many instantaneous values of an alternating current or voltage included in a complete cycle are seldom used in practical calculations and are therefore of little interest. The maximum value, the average value, and the effective value are of practical importance, especially the last named.

The *maximum value*, which is the highest value that a voltage reaches during an alternation, indicates the maximum stress to which the insulation of a device is subjected. The *average value*, or the average of the instantaneous values during an alternation, equals the maximum value multiplied by .636. The average value is used in some calculations, but not extensively. The *effective value*, sometimes called the *virtual value*, is most used; it is the one usually meant when speaking of alternating current or voltage. Effective values are meant in all further discussion unless otherwise stated.

13. The **effective value** of an alternating current has reference to its heating effect in comparison with direct current. Thus, an alternating current has an effective value of

10 amperes when it produces the same heating effect as a direct current of 10 amperes. The effective value of alternating voltage is the value corresponding to the effective current, and bears the same relation to the maximum voltage as does effective current to maximum current.

Effective voltage and effective current are indicated by all measuring instruments. The effective value of a sine-wave current or voltage is .707 times the maximum value; on the other hand, the maximum value is the indicated value divided by .707, or

$$E_e = .707\ E_m \qquad (1)$$

$$E_m = \frac{E_e}{.707} = 1.414\ E_e \qquad (2)$$

in which E_e = effective volts;
E_m = maximum volts.

EXAMPLE.—A voltmeter connected to an alternating-current circuit indicates 6,600 volts. What is the maximum value of the generated electromotive force?

SOLUTION.—According to formula **2**,

$$E_m = \frac{6{,}600}{.707} = 9{,}335 \text{ volts. Ans.}$$

14. **Phase Relations.**—When two alternating currents vary in exact unison, passing through corresponding instan-

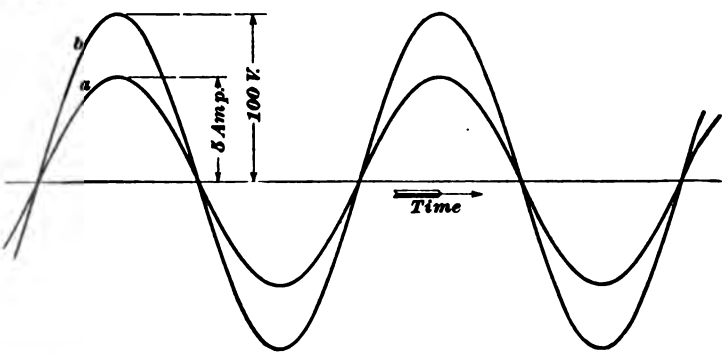


FIG. 4

taneous values, as zero, maximum, etc., together, the currents are said to be *in phase*, or *in step*. If they have the same

frequency, but do not pass through corresponding instantaneous values together, they are said to be *out of phase*. The same statements apply to two alternating voltages or to a voltage and a current.

In Fig. 4, the curve *a* represents a current of the maximum value, 5 amperes, and the curve *b*, a voltage of the maximum value, 100 volts; the current and voltage are in phase, or in step, with each other. Fig. 5 represents the same voltage and current out of phase with each other; that is, corresponding instantaneous values, such as zero and maximum values, do not occur

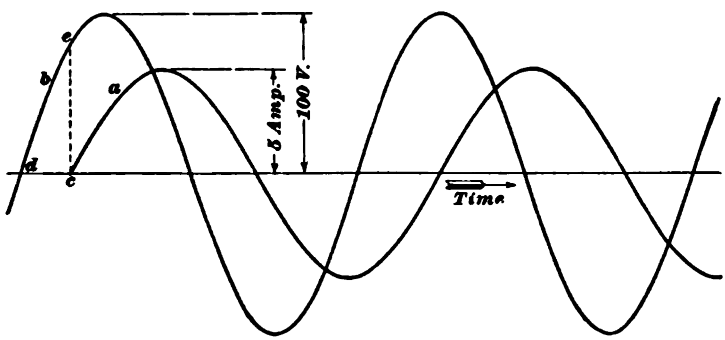


FIG. 5

simultaneously. As time is measured along the horizontal axis in the direction shown by the arrow, point *c* represents a later instant than point *d*, or curve *a* does not start until curve *b* has reached the value represented by the vertical line *c e*. The current represented by curve *a* is therefore said to *lag* behind the voltage curve *b*, though it is just as correct to say that the voltage is *leading* the current.

15. The phase difference is the number of time-degrees between two regularly varying quantities, or variables, such as an alternating voltage and its resulting current. The phase difference is called an *angle of lag* when speaking of the lagging variable and an *angle of lead* when speaking of the leading variable.

For example, Fig. 6 shows a phase difference of 60 time-degrees between the voltage represented by the curve *A* and

the current represented by the curve B; that is, the current lags behind the voltage by an angle of 60 time-degrees, and, similarly, the voltage leads the current by the same angle. In practice it is usually understood that the current is lagging when the phase difference is referred to as the angle of lag,

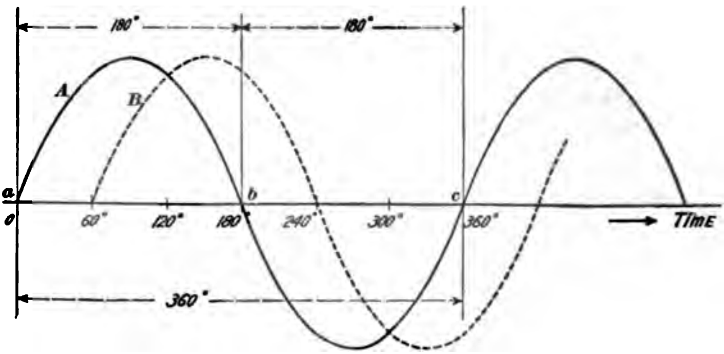


FIG. 6

or that the current is leading when the phase difference is referred to as the angle of lead.

When the phase difference between two equal currents or voltages is 180 time-degrees, they are said to be in *direct opposition* to each other. This condition is shown in Fig. 7. When a voltage (or a current) represented by the curve a is exactly maximum positive, that represented by the curve b is maximum negative; therefore, they counterbalance, or neutralize, each other and their combined effect on the circuit is zero.

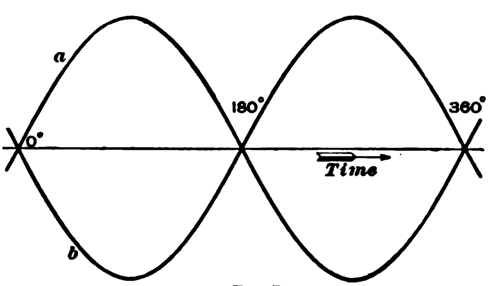


FIG. 7

16. Synchronism.—When the currents from two alternators have the same frequency and are in phase with each other, the two machines are said to be *in synchronism*. The process of adjusting the speeds of alternators for synchronism

is called *synchronizing;* and an instrument that indicates when perfect synchronism is reached is known as a *syncroscope.* Alternators must always be synchronized and their voltages equalized before connecting them in parallel with each other.

EXAMPLES FOR PRACTICE

1. A voltmeter connected to an alternating-current circuit indicates 10,000 volts. What is the maximum voltage stress to which the insulation of the circuit is subjected? Ans. 14,144 volts, approx.

2. If an alternating current of 10 amperes is maintained for 5 minutes in a resistance of 21.1 ohms, what quantity of heat in British thermal units is produced? Ans. 600 B. T. U.

NOTE—Joules = watt-seconds = $I^2R\times$seconds; 1,055 joules = 1 B. T. U.

3. Two currents are out of phase. When one is maximum positive, the other is zero. What is the phase difference between these currents? Ans. 90 time-degrees

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SELF-INDUCTION

17. The value of the magnetic flux around any conductor depends on the strength of the current. Any change in the current causes a corresponding change of flux, and the change of flux induces in the conductor an electromotive force of such a direction as to oppose and retard the change of current. Because of its opposing character, this induced electromotive force is called the *counter-electromotive force of self-induction.*

When an alternating electromotive force increases from zero to maximum, this counter-electromotive force prevents the simultaneous increase of the current. When the voltage decreases from maximum to zero, the counter-electromotive force prevents the simultaneous decrease of the current. The increase or decrease of the current is thus retarded relative to the change of voltage, and the current reaches the maximum or zero values later than the voltage, or the current lags behind the voltage.

18. The **inductance** of a circuit is the ability with which magnetic flux can be established around it by an electric

current. Inductance therefore depends on the reluctance of the path for the magnetic flux due to the current, and the induced counter-electromotive force depends on the rapidity with which that flux varies.

For example, in a coil of wire C, Fig. 8, surrounded by air, the magnetic circuit is of high reluctance and the value of the flux is correspondingly small; the inductance of such a coil is therefore low. If the coil is surrounded by magnetic material M, Fig. 9, the value of the flux set up by the same current is considerably greater, and the inductance therefore higher. If the flux in both coils is allowed to decrease to zero in 1 second, the rate of change in the number of lines in the second coil will be greater than that in the first coil because of the greater flux. Since induced voltage is proportional to the rate of change of magnetic flux, greater counter-electromotive force is induced in the second coil.

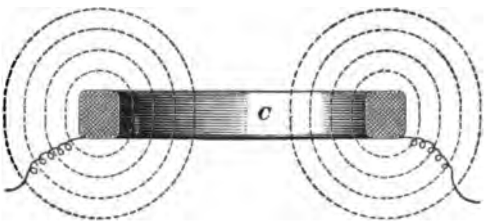


FIG. 8

The inductance of a given piece of apparatus may be considered constant when air or any material of constant permeability surrounds the conductors. If iron is present, as in case of the coil shown in Fig. 9, the inductance will be nearly constant until the magnetization approaches the saturation point.

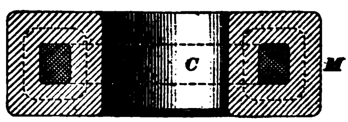


FIG. 9

Circuits that have practically no inductance are known as *non-inductive circuits;* liquid resistances and incandescent lamps are practically non-inductive.

19. The *unit of inductance* is the **henry**; 1 henry is the inductance of a circuit in which current change at the rate of 1 ampere per second will induce 1 volt of counter-electromotive force. A coil of one turn has an inductance of 1 henry

when a current of 1 ampere passing through it sets up a flux of 100,000,000, or 10^8, lines of force, because change of magnetic flux in a circuit at the rate of 10^8 lines of force per second induces 1 volt.

The henry is too large for measuring inductances found in practice, for which reason the **millihenry**, $\frac{1}{1000}$ henry, is much used. In problems, however, the value of inductance must always be expressed in henrys on account of the relation of the henry to the ampere and the volt. Thus, in calculations, 20 millihenrys should be expressed as .020 henry. The number expressing the inductance of a circuit is called the *coefficient of self-induction*.

20. The **inductive reactance** of an alternating-current circuit is that part of the apparent resistance caused by inductance, and is always expressed in ohms. Inductive reactance not only limits the current in the circuit, but also causes it to lag behind the voltage. The value of inductive reactance is 2π times the product of the frequency and the inductance, when $\pi = 3.1416$.

Let X_s = inductive reactance, in ohms;
f = frequency, in cycles per second;
L = inductance, in henrys.

Then,
$$X_s = 2\pi f L$$

EXAMPLE 1.—On a 60-cycle circuit, what is the inductive reactance of a coil having an inductance of 25 millihenrys?

SOLUTION.— 25 millihenrys = .025 henry.
$X_s = 2 \times 3.1416 \times 60 \times .025 = 9.425$ ohms. Ans.

EXAMPLE 2.—If the inductive reactance of an electrical device is 5 ohms on a 25-cycle circuit, what is its inductance?

SOLUTION.— $5 = 2\pi \times 25 \times L$, or
$$L = \frac{5}{2\pi \times 25} = \frac{5}{157.1} = .032 \text{ henry, or 32 millihenrys (nearly). Ans.}$$

21. The **inductive reactance voltage drop** is the applied voltage necessary to overcome the induced counter-electromotive force in an inductive circuit. This voltage drop is found

by a formula similar to that used for finding voltage drop in direct-current circuits, namely,

$$U_s = I X_s$$

in which U_s = inductive reactance voltage drop, in volts;
I = alternating current, in amperes;
X_s = inductive reactance, in ohms.

EXAMPLE.—A device having an inductance of .02 henry and a full-load current rating of 16 amperes is connected with a 60-cycle circuit; what is the applied voltage necessary to overcome the counter-electromotive force of the device at: (*a*) one-fourth load? (*b*) one-half load? (*c*) three-fourths load? and (*d*) full load?

SOLUTION.—According to the formula of Art. **20**,

$$X_s = 2 \times 3.1416 \times 60 \times .02 = 7.54 \text{ ohms, approx.}$$

According to the formula of this article,

(*a*) $U_s = 4 \times 7.54 = 30.16$ volts. Ans.
(*b*) $U_s = 8 \times 7.54 = 60.32$ volts. Ans.
(*c*) $U_s = 12 \times 7.54 = 90.48$ volts. Ans.
(*d*) $U_s = 16 \times 7.54 = 120.64$ volts. Ans.

22. Phase Relations in Inductive Circuits.—In Fig. 10, curve *a* represents an alternating current, and curve *b* the magnetic flux due to that current. The flux increases and decreases simultaneously with the current; hence, the current and the flux caused by it are in phase. The flux varies

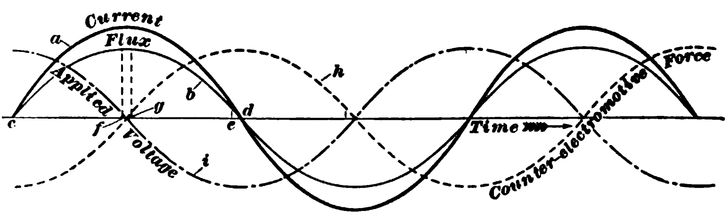


FIG. 10

most rapidly when passing its zero values, or points *c* and *d* on curve *b*, as can be seen by considering two equal time intervals *e d* and *f g*; from *e* to *d*, the change of flux is considerable, while from *f* to *g* the number of lines is nearly constant. Consequently, when the current and the flux pass through zero, the counter-electromotive force is maximum, making the

phase difference between the current and the counter-electromotive force 90 time-degrees; that is, the counter-electromotive force lags 90° behind the current and is represented by the curve *h*. The applied voltage to overcome this counter voltage must be in direct opposition to it and of

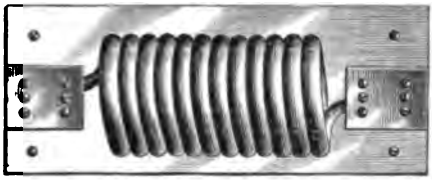


FIG. 11

the same effective value; that is, the reactive voltage drop is 90 time-degrees ahead of the current and is represented by the curve *i*, 180 time-degrees from the counter-voltage curve *h*, or in direct opposition to it.

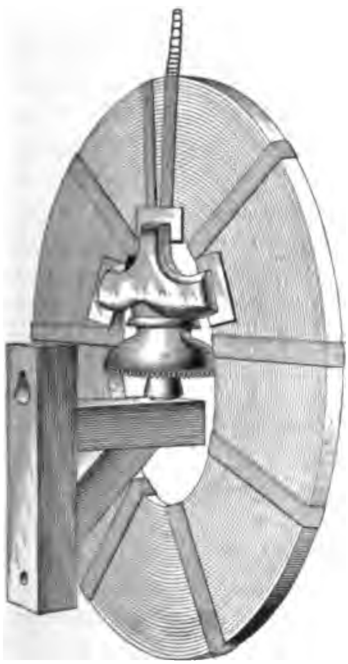


FIG. 12

23. Choke Coils.—Every circuit is at times subject to high voltage stresses of very high frequency that are caused mainly by lightning discharges or by the voltages of self-induction induced by any sudden and considerable change of current, as when opening or closing a switch. To lessen the chance of damage to apparatus by these voltage stresses, inductive devices, known as *choke*, or *reactance*, *coils*, are connected in series with the apparatus.

Choke coils are ordinary coils of wire, of either the solenoid or the spiral type, shown in Figs. 11 and 12, with high-grade insulation between the turns. These coils are designed for a specified frequency, so that the inductive reactance is comparatively negligible; but with high-frequency currents the reactance greatly increases, thus protecting the apparatus. Choke coils wound

on iron cores are connected in series with some devices, mainly arc lamps, to reduce the voltage across the device; part of the applied voltage across the two is required to overcome the counter-electromotive force induced in the reactance coil.

EXAMPLES FOR PRACTICE

1. A choke coil having an inductance of 59 millihenrys is connected to a 60-cycle system. What is the inductive reactance of the coil?
Ans. 22.24 ohms

2. What is the voltage across the terminals of a choke coil having an inductive reactance of .01 ohm, when the current through the coil is 800 amperes?
Ans. 8 volts

CAPACITY

24. Alternating voltage applied to a condenser alternately charges and discharges it; an ammeter connected in the circuit indicates the presence of current, though the plates of the condenser are actually insulated from each other. This current is known as a *charging current*, because it is the current that is alternately taken up and discharged by the condenser. A long transmission line or a long stretch of underground cable acts as a condenser of considerable capacity; if an alternating voltage is applied to either of these condensers, the ammeter will indicate a current, even though there is no load connected to the line and no appreciable leakage to the ground.

When charging a circuit containing capacity effect only, the nature of the counter-electromotive force is such that the charging current leads the applied voltage by 90 time-degrees. In this characteristic, capacity effect is exactly the opposite of inductive effect, because the latter causes the applied voltage to lead the current by 90 time-degrees. When both inductance and capacity are present in a circuit, their effects tend to balance each other.

Units of capacity were explained in *Electricity and Magnetism*, Part 2

25. The **condensive reactance** of an alternating-current circuit is that part of the apparent resistance caused by capacity; it is expressed in ohms. Condensive reactance limits the current

and causes it to lead the voltage. The value of condensive reactance is the reciprocal of the product of 2 π, the frequency, and the capacity, where $\pi = 3.1416$.

Let X_c = condensive reactance, in ohms;
f = frequency, in cycles per second;
C = capacity, in farads

Then,
$$X_c = \frac{1}{2\pi f C}$$

EXAMPLE.—A condenser having a capacity of .1 microfarad (.0000001 farad) is connected to a 25-cycle system. What is its condensive reactance?

SOLUTION.—According to the formula,
$$X_c = \frac{1}{2 \times 3.1416 \times 25 \times .0000001} = 63{,}661 \text{ ohms, approx. Ans.}$$

26. The **condensive reactance voltage drop** is the applied voltage necessary to overcome the counter-electromotive force caused by capacity effect.

Let U_c = condensive reactance voltage drop;
I = current;
X_c = condensive reactance.

Then,
$$U_c = I X_c$$

EXAMPLE.—A condenser having a capacity of .3 microfarad (.0000003 farad) and connected with a 60-cycle circuit receives a charging current of 2 amperes. What is the condensive reactance voltage drop?

SOLUTION.—According to the formula of Art. **25**,
$$X_c = \frac{1}{2 \times 3.1416 \times 60 \times .0000003} = 8{,}841 \text{ ohms;}$$
therefore, according to the formula of this article,
$$U_c = 2 \times 8{,}841 = 17{,}682 \text{ volts. Ans.}$$

EXAMPLES FOR PRACTICE

1. What is the value of the condensive reactance in a 60-cycle circuit if the capacity of the condenser is 15 microfarads?

Ans. 176.8 ohms, approx.

2. What is the capacity, in microfarads, of a 22,000-volt, 25-cycle line, if the charging current is .11 ampere, the effect of the line resistance being neglected? Ans. .03183 microfarad

NOTE.—Consider the line as a condenser, the condensive reactance voltage drop of which is 22,000; find the condensive reactance X_c by applying the formula of Art. **26**, and substitute it in the formula of Art. **25**.

CALCULATIONS WITH WAVE FORMS

27. Addition of Sine Waves in Phase.—The method of adding two alternating currents or voltages in phase, and represented by sine curves, is shown in Fig. 13. One current has the maximum value I, and is represented by the dotted curve; the other current has the maximum value I_1, and is represented by the dot-and-dash curve. The curve representing the sum is shown in full line and is found by adding the instantaneous values of the separate currents, which may be called *components of the sum.*

For example, take any instant, say a, on the zero axis. The ordinate, or vertical, $a\,b$ represents the instantaneous

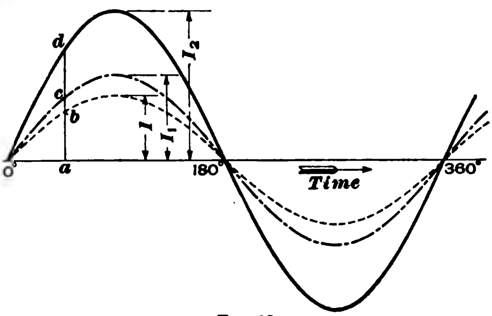


FIG. 13

value of the current I, and the ordinate $a\,c$, the instantaneous value of the current I_1. The value of their sum at this particular instant is found by adding the ordinates $a\,b$ and $a\,c$, giving $a\,d$, and thus locating the point d. Similarly, other points at different instants are determined, and the resultant curve, shown by a full line, is drawn through these points, giving a curve with maximum value $I_2 = I + I_1$. This resultant curve is also a sine curve, and its position indicates that the resultant is in phase with the two components.

28. Addition of Sine Waves Out of Phase.—The method of adding sine waves out of phase is shown in Fig. 14. Two alternating currents are represented by the curves I and I_1, current I lagging behind current I_1 by an angle represented

by the distance $b\,a$ on the zero axis. In this case, at some instants, the ordinates of the two component curves have opposite signs, one positive and the other negative. Hence, the addition of ordinates must be algebraic; that is, when both component ordinates are positive or both negative, their sum

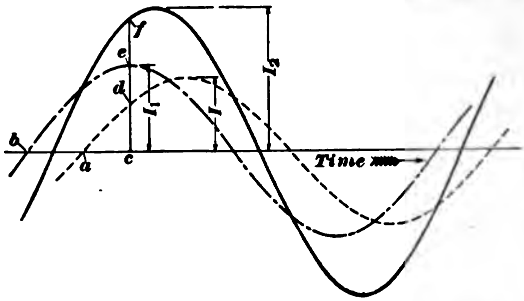


FIG. 14

is an ordinate of the resultant curve, as $c\,d + c\,e = c\,f$; again, when one component ordinate is positive and the other negative, their difference is the ordinate of the resultant curve. The resultant I_2 is a sine curve of the same frequency as the component curves, but not in phase with either of them; its maximum value is less than the sum of the maximum values of I and I_1.

29. Irregular Shapes of Waves.—The assumption that variations of an alternating current or voltage follow a sine

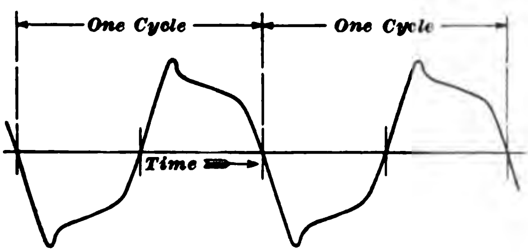


FIG. 15

curve is accurate enough for practical problems; in many cases, however, the actual shape of curves, as determined by means of an oscillograph or by some other method, differs from a

sine curve. For example, an oscillograph record may indicate the shape of curves similar to those shown in Figs. 15 and 16.

Whatever may be the shape of the curve, it is in most cases symmetrical with regard to the zero axis; that is, the positive half wave has the same shape as the negative half wave. The shape of the wave depends on the shape of the poles and some other features of the design.

30. **Harmonics.**—Any distorted curve may be considered as a resultant of a sine curve of the same frequency as the distorted curve, combined with a number of other sine curves of a higher frequency. The sine wave of the same frequency as the distorted wave is called the *fundamental wave*, and the higher frequency components are called *harmonics*. Theoretically, each distorted wave is composed of the fundamental wave and an infinite number of harmonics. Practically,

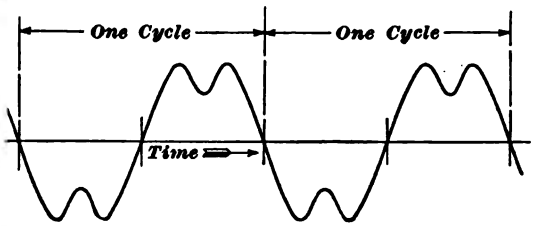


FIG. 16

however, the resultant of the fundamental and a limited number of harmonics will represent any distorted wave with sufficient accuracy.

Harmonics are distinguished by the ratio of their frequency to that of the fundamental. If double the fundamental frequency, they are called *second harmonics;* if three times, they are *third harmonics;* if four times, they are *fourth harmonics;* and so on. When a distorted curve is symmetrical with regard to the zero axis, none of its components is an *even harmonic* (second, fourth, sixth, eighth, etc.). In such a case, the distorted curve consists of the fundamental wave and *odd harmonics* (third, fifth, seventh, ninth, etc.).

31. In practice, the problem is usually that of splitting up a given distorted curve into the fundamental and harmonics.

The practical way of doing this is by means of the device known as the *wave analyzer*, with which any harmonic can be separated from a distorted curve by tracing the latter with a pointer attached to the device.

32. The ability to distinguish at a glance the presence of prominent harmonics in any distorted curve can be attained

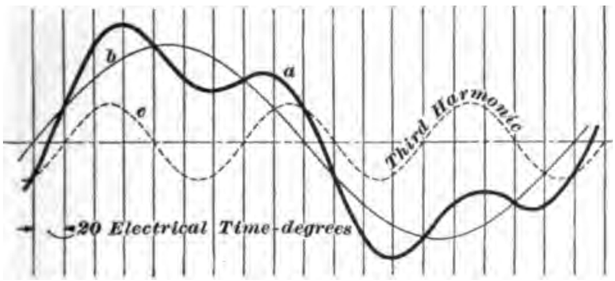


FIG. 17

only by practice in drawing different fundamental waves and harmonics and adding these algebraically, as in Figs. 17, 18, and 19. In making such drawings, the maximum value of the harmonics should be taken at less than the maximum value of the fundamental.

Fig. 17 shows the resultant curve *a* consisting of the fundamental wave *b* and the third harmonic *c*. The maximum

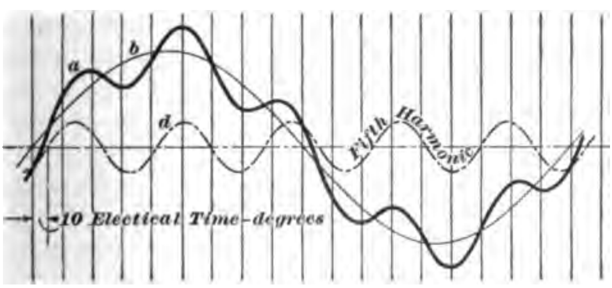


FIG. 18

value of the harmonic is taken at 40 per cent. that of the fundamental, and the phase difference between them is 20 electrical time-degrees. The ordinate of each point of

curve *a* equals the sum of the ordinates of the corresponding instantaneous points of curves *b* and *c*. Fig. 18 shows the resultant *a* of the fundamental wave *b* and the fifth harmonic *d*. The maximum value of the fifth harmonic is taken at 25 per

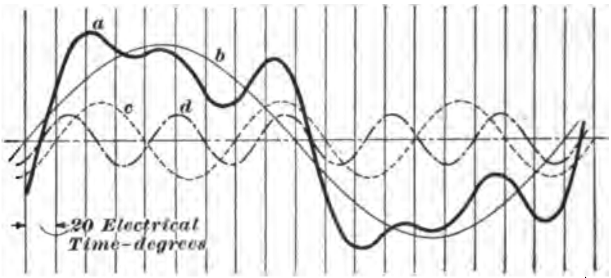


FIG. 19

cent. of the fundamental, and the phase difference is 10 electrical time-degrees. Fig. 19 shows the resultant *a* of the same fundamental *b* and the harmonics *c* and *d* shown in Figs. 17 and 18. In every case, the maximum value of the distorted curve is greater than the maximum value of the fundamental.

ALTERNATING-CURRENT CONDUCTORS AND CIRCUITS

33. Skin effect is a name given to the cause of increased resistance of a conductor to alternating current above the resistance to direct current. This increase is due to the fact that alternating current seeks the outside of a conductor, thus reducing the effective cross-section. Skin effect depends on the frequency, on the cross-sectional area of the conductor, and on the permeability. At low frequency, in small copper conductors, the skin effect is negligible; but at high frequency or with large conductors it is sometimes important. In steel rails, used as conductors, for example, the resistance is considerably greater with alternating current than with direct current. Large copper conductors are usually stranded so as to decrease the skin effect.

34. Fig. 20 shows factors, or *skin-effect coefficients*, by which to multiply the resistance of solid conductors as given in tables, or as measured with direct current, in order to obtain

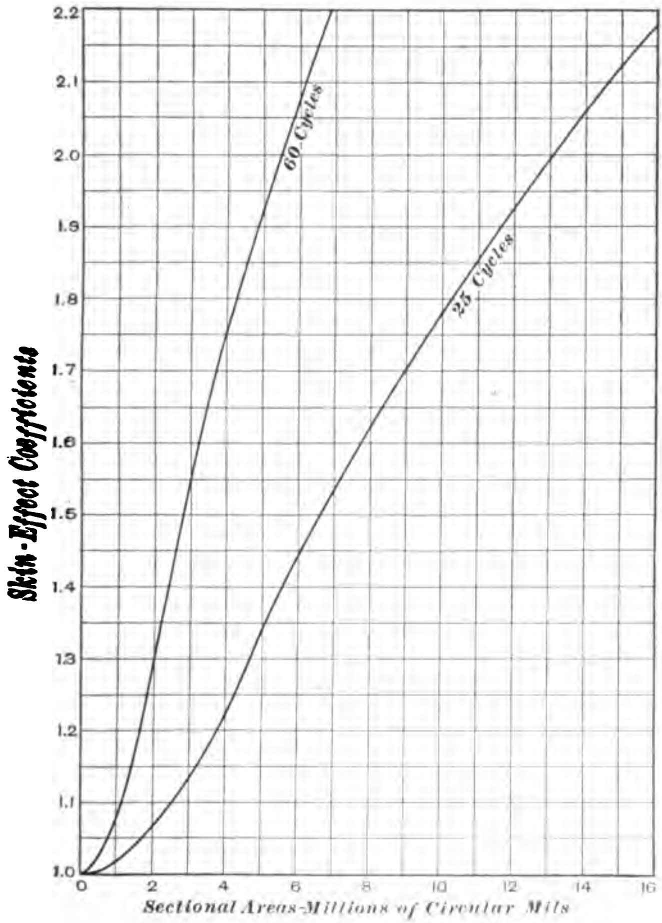


Fig. 20

the resistance to alternating current. To find the coefficient for any conductor find on the curve the point vertically above the sectional area of the conductor, and follow the horizontal line from this point to the left-hand margin. For example,

to find the coefficient for a six-million circular-mil conductor, follow the vertical line from the number *6* at the bottom to the 25- or the 60-cycle curve, as the case may be; then follow the horizontal line to the left-hand margin, where the value 1.44 is given for 25 cycles and 2.08 for 60 cycles.

Let R_a = resistance of a conductor to alternating current;
R_c = resistance to direct current;
K = skin-effect coefficient as given by the curves.

Then, $$R_a = KR_c$$

EXAMPLE.—If the resistance of a 5,000,000-circular-mil conductor to direct current is .001 ohm, what is its resistance to 60-cycle alternating current?

SOLUTION.—The skin-effect coefficient, as read from the curve, Fig. 20, is 1.92; by applying the formula,

$$R_a = 1.92 \times .001 = .00192 \text{ ohm. Ans.}$$

35. The **impedance** of a circuit is its total opposition to alternating current, including resistance, inductive reactance, condensive reactance, and skin effect. Each of the first three components has a distinct influence on nearly all alternating-current circuits; the last named is of importance only with high frequencies and large solid conductors. The law of alternating-current circuits is similar to Ohm's law for continuous-current circuits, as is shown in the following formulas:

$$I = \frac{E}{Z} \quad (1)$$

$$E = IZ \quad (2)$$

$$Z = \frac{E}{I} \quad (3)$$

in which Z = impedance, in ohms;
E = number of volts;
I = current, in amperes.

36. Circuits With Resistance Only.—The effect of resistance alone in an alternating-current circuit is the same as in a continuous-current circuit. The current is limited by the resistance according to Ohms law, $I = E \div R$, but no

phase displacement results. For example, incandescent lamps are practically non-inductive, and the current in a lighting load is therefore approximately according to Ohm's law, whether direct or alternating.

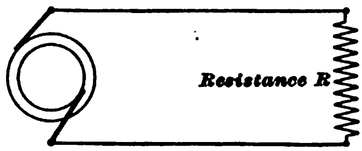


FIG. 21

In diagrams, resistance is usually represented by a zigzag line, as in Fig. 21; the circles represent the collector rings of the alternating-current generator.

37. Circuits With Inductance Only.—The current I established by an alternating voltage E in a circuit consisting of inductive reactance only (resistance and condensive reactance negligible) is in accordance with the formula

$$I = \frac{E}{X_s},$$

in which X_s is the inductive reactance. As the circuit is purely inductive, the current lags 90 time-degrees behind the voltage, or the angle of lag is 90. For example, in a coil having an inductive reactance of 10 ohms (negligible resistance and capacity), 300 volts of alternating current would establish a current of $300 \div 10 = 30$ amperes. Inductive reactance is usually indicated as shown in Fig. 22.

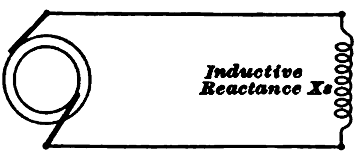


FIG. 22

38. Circuits With Capacity Only.—The current I established by an alternating voltage E through a condenser (resistance and inductive reactance negligible) is in accordance with the formula

$$I = \frac{E}{X_c},$$

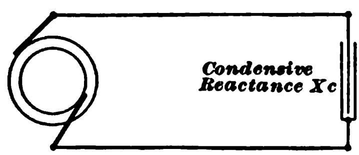


FIG. 23

in which X_c is the condensive reactance, as in Fig. 23. The current leads the voltage by 90 time-degrees, or the angle of

lead is 90. For example, if the voltage is 300 and the condensive reactance 1,500 ohms, with no resistance or inductive reactance, the current is $300 \div 1,500 = .2$ ampere.

EXAMPLES FOR PRACTICE

1. A round copper bar having an area of 4,000,000 circular mils is used as a conductor on a 60-cycle alternating-current system. How much does the skin effect increase the resistance of this bar? Ans. 1.75 times

2. The voltmeter and ammeter connected to an alternating-current circuit give readings of 440 volts and 80 amperes, respectively. What is the impedance of the circuit? Ans. 5.5 ohms

3. A device, the inductance of which is .1273 henry, the resistance being negligible, is connected across a 220-volt circuit of a 25-cycle system. What is the current value through the device? Ans. 11 amp.

VECTORIAL REPRESENTATIONS

39. Vectors.—The values of quantities and forces can be represented by straight lines; thus, 10 amperes can be represented by a line $\frac{1}{8}$ inch long, 20 amperes by a line $\frac{1}{4}$ inch long, etc., the length of the line being proportional to the value represented. For example, if 150 volts is represented by a line $\frac{1}{16}$ inch long 6,600 volts must be represented by a line $\frac{6,600}{150} \times \frac{1}{16} = 2\frac{3}{4}$ inches long.

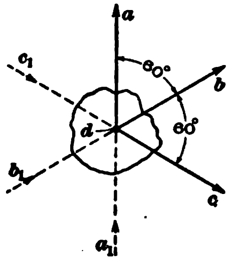


FIG. 24

The positions, or directions, of these lines may also be used to represent the relative directions of currents and voltages. For example, two voltages exactly opposing each other may be represented by two straight lines drawn in opposite directions from a common point. Lines used to represent both value and direction are called *vectors*.

40. The vectors shown in Fig. 24 represent three equal forces a, b, and c applied to a point d on a body. The directions of forces a and c are separated by 120 mechanical degrees and force b acts midway between them or 60 mechanical degrees

from each; the vectors representing these forces are, therefore, separated by these angles.

The same forces, acting in the same directions, may also be represented by the vectors shown by the dotted lines a_1, b_1, and c_1; the arrowheads, however, instead of pointing outwards from the point d, point toward it. In the first case, the forces may be imagined as pulling forces, acting on the body, and in the second case they may be imagined as pushing forces, acting on the body. As it is immaterial whether the body is pushed or pulled in a given direction, the resulting force and its direction will be the same in both cases.

For example, if two forces are acting at a point, one pulling horizontally 60 pounds and the other pushing vertically down-

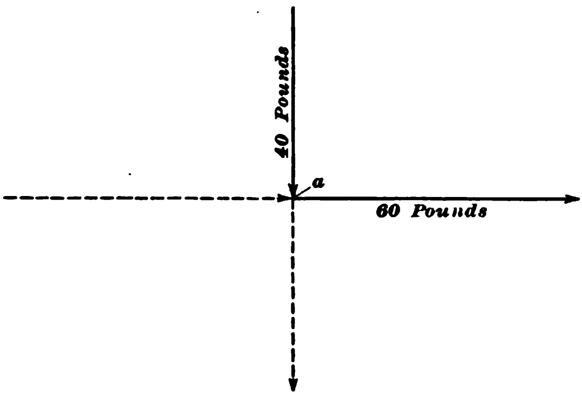


Fig. 25

wards 40 pounds, these forces can be represented by vectors, as in Fig. 25. If $\frac{1}{8}$ inch represent 5 pounds, the horizontal force acting at the point a will be represented by a line $1\frac{1}{2}$ inches long and the vertical force by a line 1 inch long. The vertical force could also be represented as pulling downwards from the point a, and the horizontal force as pushing from the left, as indicated by the arrowheads on the dotted vectors.

41. Addition of Vectors.—When two or more forces act in the same direction, the resulting force is equal to the sum of these forces. In Fig. 26 the vectors a and b represent

two forces, 3 and 4 pounds, respectively, acting in the same direction. If both act from the same point, the resulting force is a pull of $3+4=7$ pounds in the direction of the components, and is represented by the vector *c*. The sum, therefore, is found by placing one vector at the end of the other, having due regard to their direction.

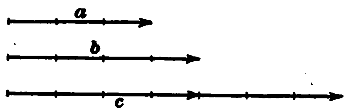


Fig. 26

If two forces act in different directions, the resultant force is represented both in value and direction by the diagonal of the parallelogram of which the vectors of the component forces form two adjacent sides, this diagonal passing through the common point of the two vectors. This figure is called the *parallelogram of forces*. For example, Fig. 27 shows a cord passing over fixed pulleys *a* and *b* and having weights hung from the ends and the center, the center weight hanging from a loose pulley *c* running on the cord. With the pulleys *a* and *b* placed as shown, a center weight of 5 pounds balances end weights of 3 and 4 pounds; the lines *a c*, *b c* and *d c* are proportional to 3, 4, and 5, respectively, and *d c* is the diagonal of the parallelogram, completed as shown by the dotted lines, of which *a c* and *b c* are two adjacent sides.

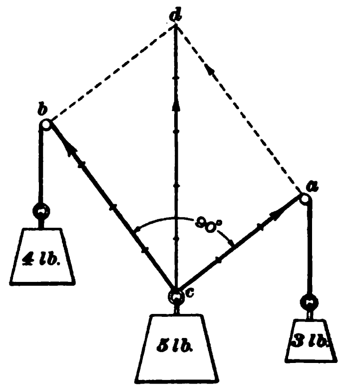


Fig. 27

Fig. 28 shows the method of adding two vectors *a* and *b*, giving the resultant vector *c*, which is one diagonal of the parallelogram. The two component vectors are first placed so as to act from a point *o*; the parallelogram is completed and the diagonal drawn from the same point *o*.

42. The *triangle of forces* affords a practical method of determining the resultant, or the sum of vectors, somewhat shorter than by the parallelogram of forces. Another reference

to Fig. 27 will show that the line *a d* is of the same length as the line *c b* and parallel to it; the force represented by the line *c b* may therefore be represented by the line *a d*, provided there is placed on the latter an arrowhead pointing in the same direction as that on the line *c b*. Thus, in the triangle *c a d*, the side *c a* represents one component vector and the side *a d* the other, while the third side *c d* represents the resultant vector. The sum of any two vectors may be similarly determined by placing the beginning of one vector at the end of the other, without changing their relative directions. The line that joins the free ends of the vectors and completes the triangle is the resultant vector.

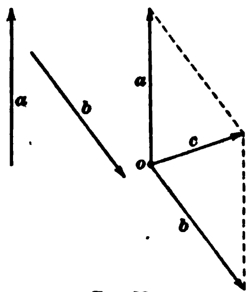


FIG. 28

The example shown in Fig. 28 may be solved as shown in Fig. 29, the lettering of the vectors being the same.

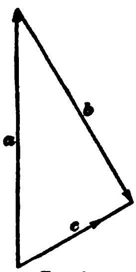


FIG. 29

On tracing around any triangle in the direction of the arrowheads on the component vectors, the arrowhead on the resultant vector should point opposite to the direction of tracing; this method of indicating directions of vectors shows that the resultant balances the effects of the components. For example, the resultant of the vectors *a* and *b*, Fig. 30, will be the vector *c*, and the arrowhead on this vector will point as shown in the illustration.

To determine the phase relations of varying quantities, their vectors must be considered as acting from a point. For example, in Fig. 30, the correct phase relations are shown by drawing vector *b* in its true position, as shown by the dotted line b_1, equal and parallel to vector *b*, and indicating by its arrowhead the same direction of action.

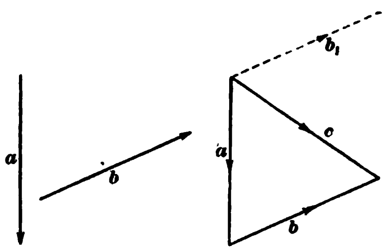


FIG. 30

EXAMPLE 1.—What is the sum of two forces of 24 and 32 pounds, respectively, acting at right angles to each other?

SOLUTION.—Assuming a line $\frac{1}{32}$ in. long to represent a force of 1 lb., the vectors are indicated as acting from the point o, Fig. 31. The vector indicated by the dotted line is then transferred to position $a\ b$. The resultant vector measures $1\frac{1}{4}$ in., which represents $1\frac{1}{4} \div \frac{1}{32} = 40$ lb. Ans.

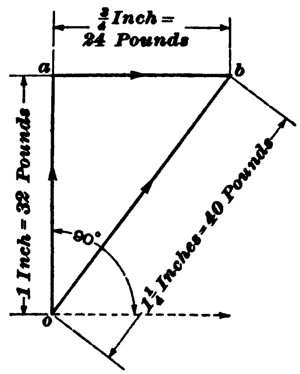


FIG. 31

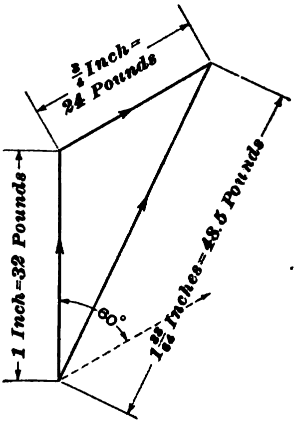


FIG. 32

EXAMPLE 2.—What is the sum of the same two forces, as in example 1, acting in directions 60° from each other?

SOLUTION.—Assuming a line $\frac{1}{32}$ in. long to represent a force of 1 lb., the vectors are drawn as shown in Fig. 32. The length of the resultant is $1\frac{33}{64}$ in., approximately, and this represents $1\frac{33}{64} \div \frac{1}{32} = 48.5$ lb. Ans.

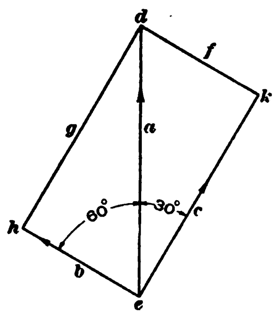


FIG. 33

43. Resolution of Vectors. The operation of finding component vectors that when added together will make up a given resultant vector is called the *resolution of vectors*. These components can be found by constructing a parallelogram with the resultant vector as one of the diagonals. The two sides of the parallelogram, uniting at one end of the resultant vector, are the desired component vectors.

For example, to resolve the vector a, Fig. 33, into two components, one 60° and the other 30° away from the resultant,

lines b and c are drawn from the point e, one inclined 60° to the resultant a and the other 30°. From the end of vector a, that is, from the point d, a line f is drawn parallel to the line b and a line g parallel to the line c, cutting the lines c and b at k and h, respectively. The lines $e\,h$ and $e\,k$ are the two component vectors of the resultant vector a.

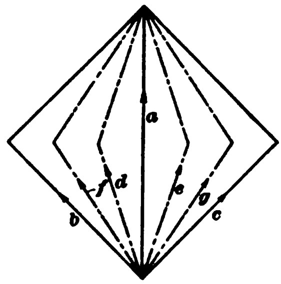


Fig. 34

44. When the directions of the component vectors are not given, an unlimited number of pairs of vectors may be drawn, such that the vectorial sum of each pair equals the given resultant vector. Thus, the vector a, Fig. 34, may be resolved into the vectors b and c, d and e, f and g, or any other pair, of which the vector a will be the sum. But when the position of the components relative to the resultant is specified, or the position and the magnitude of one of the components is given, only one solution of the problem is possible.

45. The resolution of vectors may be somewhat shortened by the triangle of forces. For example, the problem of Art. 43 may be solved as follows: From one end e on the resultant vector a, Fig. 35, draw the line b, inclined 60° to the resultant; from the other end d draw the line c inclined 30° to the resultant. The lines b and c will intersect at the point h, thereby determining the lengths of the components. The arrowheads on the component vectors b and c must point in the same general direction around the triangle and in opposition to that on their resultant vector a, for the reasons explained before. To determine phase relations, however, all vectors must be indicated as acting from one point. Thus, transferring vector c to its true position c_1 shows correct phase relations of vectors a, b, and c_1.

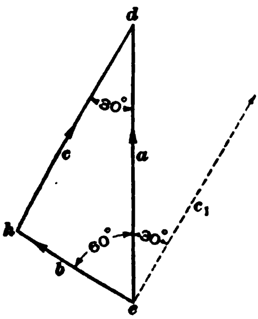


Fig. 35

Suppose a force of 50 pounds is to be resolved into two components, one 15° from the direction of the resultant and the other 30°. Any convenient length, say $\frac{1}{16}$ inch, can be assumed to represent a force of 1 pound. A force of 50 pounds must then be represented by a line $50 \times \frac{1}{16} = 3\frac{1}{8}$ inches long. Line *a*, Fig. 36, is accordingly drawn $3\frac{1}{8}$ inches long, and from its ends lines *b* and *c* are drawn to make angles of 15° and 30°, respectively, with line *a*. These lines meet at a point *d*, and their lengths are $2\frac{1}{32}$ and $1\frac{9}{64}$ inches, respectively; at $\frac{1}{16}$ inch per pound these lengths represent forces of 32.5 and 18.25 pounds.

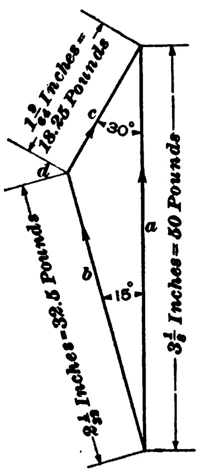


FIG. 36

46. Subtraction of vectors is the process of resolving a resultant vector into two components, one of which is known. For example, if vector *a*, Fig. 37, is the resultant and vector *b* the known component, vector *c*, completing the triangle of forces, must be the other component, or the vectorial difference between *a* and *b*. In the path around the triangle, the directions of the two components must agree and must oppose the direction of the resultant, as shown by the arrowheads.

47. Vectorial Representation of Alternating Current and Voltage. Vectors representing alternating currents or voltages can be added and subtracted in exactly the same way as the vectors of forces. Currents or voltages in phase are treated like forces acting in the same direction, and those differing in phase, like forces acting in different directions.

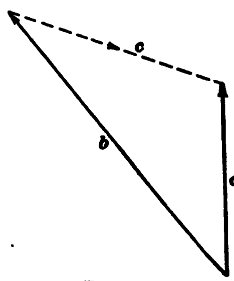


FIG. 37

For example, the sum of two currents of 3 and 4 amperes differing in phase by 90 time-degrees is 5 amperes, or numerically, the same as the sum of two forces of 3 and 4 pounds acting 90° from each other. The phase difference, in

time-degrees, between the resultant current or voltage and its components is numerically equal to the number of mechanical degrees between the resultant vector and its components. For example, in Fig. 33, if vectors b and c represent component voltages, vector a is the resultant voltage, and the phase differences between the resultant and its components are 60° and 30°, respectively, as indicated.

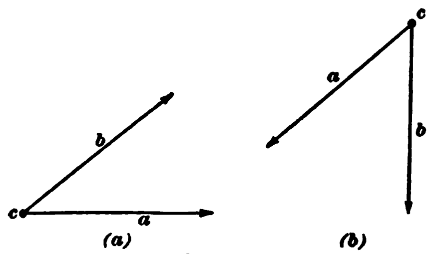


Fig. 38

48. In order to indicate angles of lead and lag, the general practice is to consider vectors as rotating counter-clockwise. Thus, vectors a and b, Fig. 38, may be considered as rotating counter-clockwise about the point c; in both views (a) and (b), vector a indicates a lagging variable quantity, and vector b a leading variable quantity.

49. Fig. 39 shows a method of adding two currents of 100 amperes each and differing in phase by 90 time-degrees. The vectors a and b representing these equal currents must be equal in length and at right angles to each other. The length of the resultant vector c, by the same scale, represents 141 amperes, and its position shows that the resultant current is 45 time-degrees behind the leading current represented by vector a and 45 time-degrees ahead of the lagging current represented by vector b.

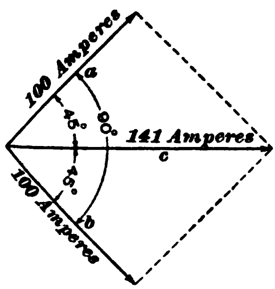


Fig. 39

50. Fig. 40 shows a method of subtracting two electromotive forces of 100 volts each and differing in phase by 120 time-degrees. The vectors a and b representing these equal electromotive forces must be of equal length and drawn to make an angle of 120°. The length of the component vector c, by the scale used

for vectors a and b, represents 173 volts, and is the same whether a is subtracted from b or b from a. The direction of vector c, however, differs in the two cases. When a is subtracted from b, the directions of a and c in the triangular path must agree and must oppose the direction of b, as is indicated by the arrowheads; that is, vectors $a+c=$ vector b. When b is subtracted from a, the directions of b and c must agree and must oppose the direction of a; that is, the arrowhead on vector c would be reversed, indicating that $b+c=a$.

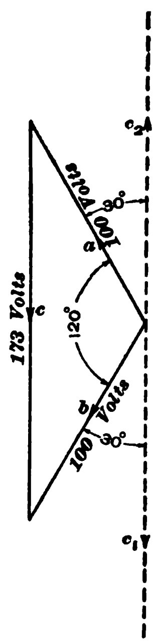


FIG. 40

When a is subtracted from b, c leads b by 30 time-degrees and a by $120+30=150$ time-degrees; these relations are indicated by placing vector c in position c_1, so as to act from the point of application of the forces, always the proper position to determine phase difference. When b is subtracted from a, the direction of c is reversed, and it must be placed in position c_2 to show phase difference; in this case c lags behind a 30 time-degrees and behind b 150 time-degrees.

EXAMPLES FOR PRACTICE

NOTE.—The following examples should be solved by means of vectors. In each case, assume any convenient scale and obtain the given angle by means of Fig. 2. To do this, draw one of the vectors of the proper length, according to the scale chosen, and lay the paper on which it is drawn over Fig. 2 so that the vector coincides with line $o\,d$; then mark off the required angle. The paper used must be thin enough to permit the lines of Fig. 2 to be seen through it. Accuracy in making measurements, and especially in laying off angles, is absolutely essential to obtain correct results.

1. Find by vectorial addition, the sum of two currents of 48 and 20 amperes and differing in phase by 90 time-degrees. Ans. 52 amp.

2. Find, by addition of vectors, the sum of two electromotive forces of 63.5 volts each and differing in phase by 60 time-degrees. Ans. 110 volts, approx.

3. Two component voltages of equal magnitude differ in phase by 90 time-degrees. Find these voltages by resolution of vectors, if their sum is equal to 440 volts. Ans. 311 volts, approx.

4. Find, by vectorial subtraction, the difference between two electromotive forces of 63.5 volts each and differing in phase by 60 time-degrees. Ans. 63.5 volts

ALTERNATING CURRENTS

(PART 2)

SINGLE-PHASE CIRCUITS

SERIES CIRCUITS

1. Resistance and Inductance in Series.—In a circuit containing both resistance R and inductive reactance X_s connected in series, as shown in Fig. 1, alternating voltage follows the general law $E = I\,Z$, in which I is the current and Z the impedance. The current in the two is the same and requires a voltage $U = I\,R$ to overcome the resistance voltage drop and a voltage $U_s = I\,X_s$ to overcome the counter electromotive force of self-induction. The resistance drop is in phase with the current, and the inductive drop leads the current by 90 time-degrees. The impressed voltage E must equal the vectorial sum of the two.

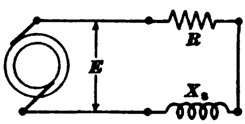


FIG. 1

The method of determining this sum is shown in Fig. 2, in which the vector $o\,b$ represents the voltage U in phase with the current, and the vector $o\,c$, the voltage U_s, 90 time-degrees ahead of the resistance voltage drop U. Their sum, or the impressed voltage E, is represented by the vector $o\,d$, the position of which shows

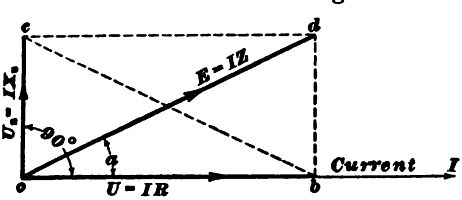


FIG. 2

that the main current lags behind the impressed voltage by the angle a in electrical time-degrees. From the values of I and E, the value of impedance Z may be determined by the general formula

$$Z=\frac{E}{I}$$

2. The resultant voltage E and its phase displacement relative to the current can be determined also by means of a triangle of forces, as shown in Fig. 3. Such a triangle is usually referred to as the *voltage and impedance triangle*, because by means of it the impedance also can be determined. The value of the current being the same throughout the circuit, the resistance and the inductive reactance are proportional to the voltages necessary to overcome them. For example, if the resistance is represented by the vector $a\,b$ and the inductive reactance by the vector $b\,c$, their resultant, or impedance, is represented by the vector $a\,c$. The value of the voltage and the impedance can be determined approximately by measuring the length of the sides of the triangle, but more accurate results are obtained by calculation, using the formulas

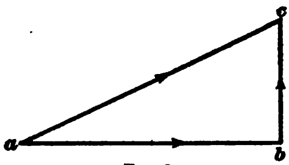


FIG. 3

$$E=\sqrt{U^2+U_s^2} \qquad (1)$$

$$Z=\sqrt{R^2+X_s^2}, \qquad (2)$$

in which E = applied voltage;

U = voltage drop in the resistance, represented by $a\,b$;

U_s = voltage to overcome counter electromotive force of self-induction, represented by $b\,c$;

Z = impedance;

R = resistance;

X_s = inductive reactance.

EXAMPLE 1.—The voltage necessary to overcome the resistance of a circuit is 64, and that to overcome the inductive reactance is 48. Find the value of the impressed electromotive force.

SOLUTION.—According to formula **1**,

$$E=\sqrt{64^2+48^2}=\sqrt{4{,}096+2{,}304}=80 \text{ volts. Ans.}$$

Example 2.—The resistance of a circuit is 4 ohms, and the inductive reactance 3 ohms. Find the impedance of the circuit.

Solution.—According to formula **2**,

$$Z = \sqrt{4^2+3^2} = \sqrt{16+9} = 5 \text{ ohms. Ans.}$$

Example 3.—A choke coil is required in series with an 80-volt arc lamp in order to connect the latter across a 120-volt, 60-cycle circuit; the current through the lamp is 4 amperes. What is the inductive reactance of the coil?

Solution.—The voltage drop across the lamp is considered as used in overcoming ohmic resistance, while the voltage across the choke coil is considered as used in overcoming inductive reactance. The vectors of the two are therefore at right angles to each other, and their sum, or the hypotenuse of the triangle, is equal to 120 volts.

According to formula **1**, $120 = \sqrt{80^2+U_s^2}$; therefore, $120^2 = 80^2+U_s^2$, and $U_s^2 = 120^2-80^2$; from which $U_s = \sqrt{120^2-80^2} = 89.44$ volts. The choke coil and the lamp are connected in series; therefore, the current through both is the same, namely, 4 amp., and the inductive reactance is

$$X_s = U_s \div I = 89.44 \div 4 = 22.36 \text{ ohms. Ans.}$$

3. Resistance and Capacity in Series.—Alternating voltage E applied to a circuit containing both a resistance R and a condensive reactance X_c, as shown in Fig. 4, establishes a current I through both. The applied voltage E is equal to the vectorial sum of the voltage $U = IR$ necessary to overcome the resistance voltage drop, and the voltage $U_c = IX_c$ necessary to overcome the counter electromotive force due to condensive reactance.

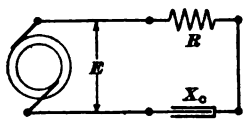


Fig. 4

The former is in phase with the current and the latter lags 90 time-degrees behind it. The method of determining this sum is shown in Fig. 5, in which the vector $o\,b$ represents the voltage U and the vector $o\,c$, the voltage U_c. The resultant voltage E is represented by the vector $o\,d$, the position of which shows that the current leads the applied voltage by the angle a in electrical time-degrees.

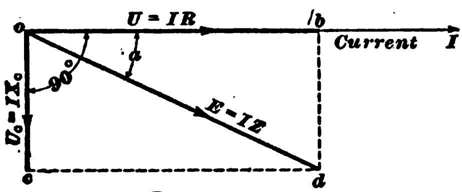


Fig. 5

The triangle method, as explained in Art. 2, can be used also, but more accurate results can be obtained by use of the following formulas:

$$E=\sqrt{U^2+U_c^2} \qquad (1)$$

$$Z=\sqrt{R^2+X_c^2} \qquad (2)$$

EXAMPLE.—A non-inductive resistance of 1,000 ohms and a condensive reactance of 1,600 ohms are connected in series across a 440-volt circuit. What is: (*a*) the impedance? (*b*) the value of the current?

SOLUTION.—(*a*) According to formula 2,

$$Z=\sqrt{1{,}000^2+1{,}600^2}=1{,}887 \text{ ohms, approx. Ans.}$$

(*b*) Transposing the general law $E=I\,Z$,

$$I=\frac{440}{1{,}887}=.233 \text{ amp., or } 233 \text{ milliamp. Ans.}$$

4. Inductance and Capacity in Series.—In a circuit containing inductive and condensive reactance *only*, with *no resistance*, as shown in Fig. 6, the effect of capacity would tend to neutralize the effect of self-induction. Component voltages of such a circuit are shown in Fig. 7, in which the vector $o\,a$ represents the current; the vector $o\,b$, the voltage $U_c=I\,X_c$ necessary to overcome the counter electromotive force of capacity; and the vector $o\,c$, the voltage $U_s=I\,X_s$ necessary to overcome the counter electromotive force of self-induction. The voltage U_c lags 90 time-degrees behind the current and the voltage U_s leads the current by 90 time-degrees.

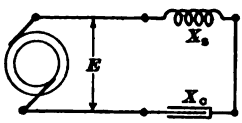


FIG. 6

The two effects neutralize completely when the power $I\,U_c$ is equal to the power $I\,U_s$. In a series circuit, in which the current through both reactances is the same, the neutralization takes place when the voltages U_s and U_c are equal. When these voltages are not equal, a part of the greater voltage neutralizes

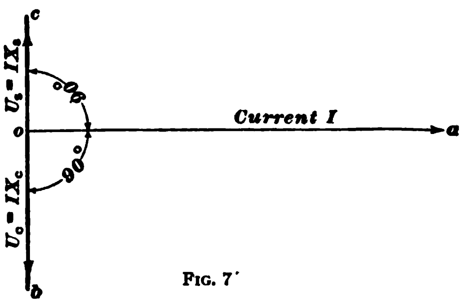


FIG. 7

the smaller voltage, and the resulting condition is that of a simple circuit possessing either inductive or condensive reactance only, according to whether U_s or U_c is the greater. The resultant voltage differs by 90 time-degrees from the current and is, in one case, $U_s - U_c$ and in the other $U_c - U_s$.

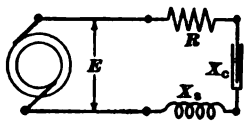


FIG. 8

Such conditions are purely theoretical; they never occur in practice, because a circuit entirely devoid of resistance is impossible. Nevertheless, a knowledge of such conditions is essential to a clear understanding of practical problems.

5. Resistance, Capacity, and Inductance in Series. A voltage E applied to a circuit containing resistance R, condensive reactance X_c, and inductive reactance X_s, as shown in Fig. 8, is equal to the sum of the voltages necessary to overcome the drop of voltage and the counter electromotive forces.

Two methods of determining this sum are shown in Fig. 9, in which the vector $o\,a$ represents the voltage $U = I\,R$; the vector $o\,b$, the voltage $U_c = I\,X_c$; and the vector $o\,c$, the voltage $U_s = I\,X_s$. One method of determining the resultant vector $o\,e$, representing the voltage E, consists in adding vectorially three electromotive forces displaced in phase by 90 time-degrees. Vectors $o\,a$ and $o\,c$ are added first, forming the resultant $o\,d$; then $o\,b$ and $o\,d$ are added, forming the resultant vector $o\,e$, which represents the impressed voltage E lagging behind the current. If U_c and U_s were equal, they would neutralize and the vectors $o\,e$ and $o\,a$ would coincide; that is, the voltage E would be in phase with the current and proportional to the resistance. The other method of finding the

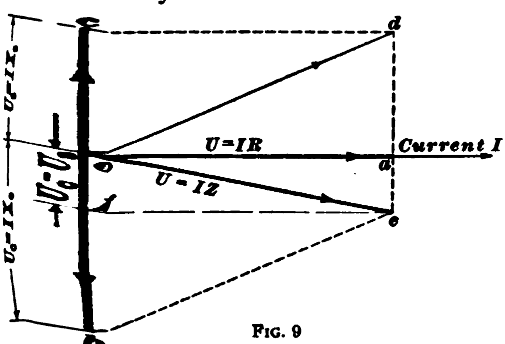


FIG. 9

vectorial sum consists in drawing the vector $o\,f$, representing the difference between the voltages U_c and U_s, in the direction of the greater of the two voltages, and then adding vectors $o\,a$ and $o\,f$. This gives the resultant $o\,e$, as before.

By using the method of calculation explained in Arts. **2** and **3**, the following relations are established:

$$E = \sqrt{U^2 + (U_c - U_s)^2} \qquad (1)$$

or

$$E = \sqrt{U^2 + (U_s - U_c)^2}, \qquad (2)$$

depending on whether U_c or U_s is the greater.

Likewise, impedances may be determined from formulas:

$$Z = \sqrt{R^2 + (X_c - X_s)^2} \qquad (3)$$

$$Z = \sqrt{R^2 + (X_s - X_c)^2}, \qquad (4)$$

depending on whether X_c or X_s is the greater.

EXAMPLE.—An alternator is connected to a circuit having a resistance of 96 ohms, an inductance of 249 millihenrys, and a capacity of 19.8 microfarads. The value of the current through the circuit is 5 amperes and the frequency is 60. (*a*) Find the drop of potential across the resistance, and the voltages necessary to overcome the effects of self-induction and capacity. (*b*) Determine whether the current leads the main voltage or lags behind it. (*c*) Find the value of the main voltage necessary to maintain the current at 5 amperes. (*d*) Find the impedance of the circuit.

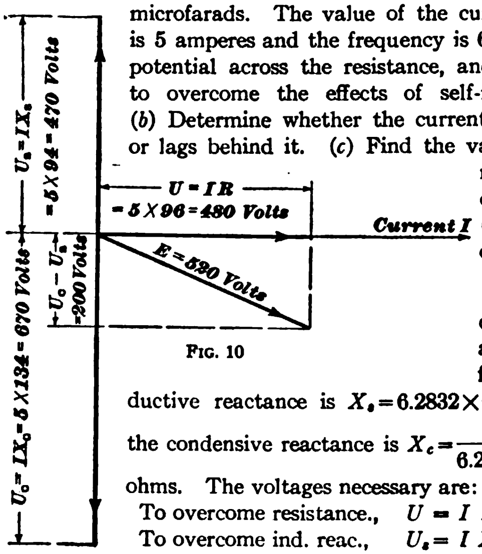


FIG. 10

SOLUTION.—(*a*) The inductance is .249 henry and the capacity .0000198 farad; therefore, the inductive reactance is $X_s = 6.2832 \times 60 \times .249 = 94$ ohms, and the condensive reactance is $X_c = \dfrac{1}{6.2832 \times 60 \times .0000198} = 134$ ohms. The voltages necessary are:

$$\left.\begin{array}{ll} \text{To overcome resistance.,} & U = I\,R = 5 \times 96 = 480. \\ \text{To overcome ind. reac.,} & U_s = I\,X_s = 5 \times 94 = 470. \\ \text{To overcome cond. reac.,} & U_c = I\,X_c = 5 \times 134 = 670. \end{array}\right\} \text{Ans.}$$

(*b*) The current must lead the voltage because the condensive reactance exceeds the inductive reactance. These relations are made clear by a vectorial diagram, Fig. 10.

(c) The value of the line voltage is determined by formula **1**. Thus,

$$E = \sqrt{480^2 + (670-470)^2} = 520 \text{ volts. Ans.}$$

(d) The value of the impedance may be determined either by formula **3**, as

$$Z = \sqrt{96^2 + (134-94)^2} = 104 \text{ ohms}$$

or by the general formula,

$$Z = \frac{E}{I} = \frac{520}{5} = 104 \text{ ohms. Ans.}$$

EXAMPLES FOR PRACTICE

1. An inductive reactance of 8 ohms in series with a non-inductive resistance of 15 ohms is connected with a 119-volt circuit. Find the value of the current. Ans. 7 amp.

2. A coil connected to a 130-volt, continuous-current circuit carries 26 amperes. The same coil connected to a 130-volt, 60-cycle, alternating-current circuit, carries only 10 amperes. What is the inductance of the coil? Ans. 31.8 millihenrys

NOTE.—From the first pair of voltage and current values, determine the resistance; from the second pair, determine the impedance. Thus, one side and the hypotenuse of an impedance triangle are determined. Find the third side, which is the inductive reactance of the coil, and from this value, knowing the frequency, determine the inductance.

PARALLEL CIRCUITS

6. Resistance and Inductance in Parallel.—A voltage E applied to the terminals of a resistance R and an inductive reactance X_s connected in parallel, Fig. 11, establishes in them the currents I_r and I_s. These currents are determined by the formulas $I_r = \frac{E}{R}$ and $I_s = \frac{E}{X_s}$, and the resultant, or the line current I is equal to their vectorial sum.

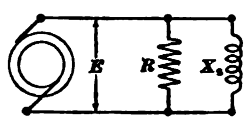


FIG. 11

The method of determining this sum is shown in Fig. 12, in which the vector $o\,a$ represents the current I_r in phase with the voltage E, and the vector $o\,b$, the current I_s lagging 90 time-degrees behind the voltage. The resultant, or the line current I, is represented

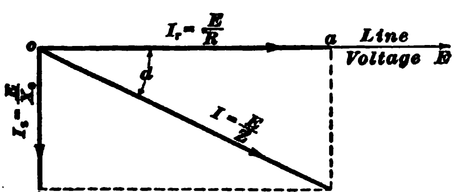


FIG. 12

by the vector *o c*, which indicates that the line current I lags behind the line voltage E by the angle d in electrical time-degrees.

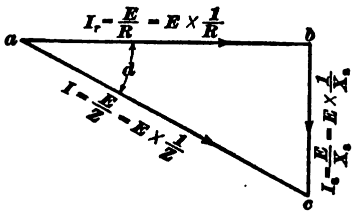


Fig. 13

7. The resultant current may be determined also by means of the triangle of forces, as shown in Fig. 13. The sides *a b* and *b c* represent the component currents, and the hypotenuse *a c* represents their vectorial sum, or the line current, lagging behind the line voltage by the angle d. By formula,

$$I = \sqrt{I_r^2 + I_s^2}$$

Example.—An alternating voltage of 220 is applied to a circuit having connected in parallel a non-inductive resistance of 18.3 ohms and an inductive reactance of 44 ohms. Determine the currents through the branches and the line current.

Solution.—The component currents are

$$I_r = \frac{220}{18.3} = 12 \text{ amp., approx.} \quad \text{Ans.}$$

$$I_s = \frac{220}{44} = 5 \text{ amp.} \quad \text{Ans.}$$

According to the preceding formula,

$$I = \sqrt{12^2 + 5^2} = 13 \text{ amp.} \quad \text{Ans.}$$

8. Conductance, Admittance, and Susceptance.—Just as the reciprocal of resistance $\frac{1}{R}$ is called *conductance*, so the reciprocal of impedance $\frac{1}{Z}$ is called *admittance* and the reciprocal of reactance $\frac{1}{X_s}$ or $\frac{1}{X_c}$, is called *susceptance*. These reciprocals express the ability with which a circuit conducts alternating current and the value of the current is proportional to them. Admittance and susceptance are expressed in the same unit as conductance, namely, the *mho*, or the word ohm spelled backwards. The admittance of a parallel circuit,

which is analogous to the joint conductance of a direct-current circuit, is found by adding vectorially the component conductances and susceptances. The impedance can then be determined by taking the reciprocal of the admittance.

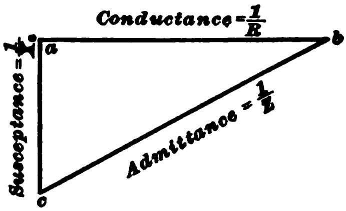


FIG. 14

The method of determining an admittance is shown in Fig. 14. If the side $a\,b$ represents the conductance and the side $a\,c$ the susceptance, the hypotenuse $c\,b$ represents the admittance; or, by formula,

$$\frac{1}{Z}=\sqrt{\left(\frac{1}{R}\right)^2+\left(\frac{1}{X_s}\right)^2}$$

EXAMPLE.—A resistance of 24 ohms and an inductive reactance of 10 ohms are connected in parallel. What is the impedance of the circuit?

SOLUTION.—The conductance is $\frac{1}{24}$ mho and the susceptance $\frac{1}{10}$ mho. According to the formula just given,

$$\frac{1}{Z}=\sqrt{\left(\frac{1}{24}\right)^2+\left(\frac{1}{10}\right)^2}=\sqrt{\frac{1}{576}+\frac{1}{100}}=\sqrt{\frac{6.76}{576}}=\frac{2.6}{24}\text{ mho}$$

If $\frac{1}{Z}=\frac{2.6}{24}$, $\quad Z=\frac{24}{2.6}=9.23$ ohms. Ans.

9. Resistance and Capacity in Parallel.—If a voltage E is applied to the terminals of a resistance and a condensive reactance that are connected in parallel, as shown in Fig. 15, the currents I_r and I_c will result in them. The value of these currents is determined by the formulas $I_r=\frac{E}{R}$ and $I_c=\frac{E}{X_c}$; the resultant, or the line current I, is equal to the vectorial sum of these currents, as illustrated in Fig. 16, in which the vector $o\,a$ represents the current I_r, in phase with the line voltage, and the vector $o\,b$ represents the current I_c through the condensive reactance, this current leading the line voltage by 90 time-degrees. The sum of these currents, or the line current I, is represented

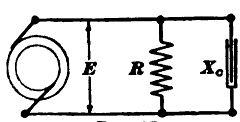


FIG. 15

by the vector oc, the position of which indicates that the line current I leads the line voltage E by the angle d in time-degrees.

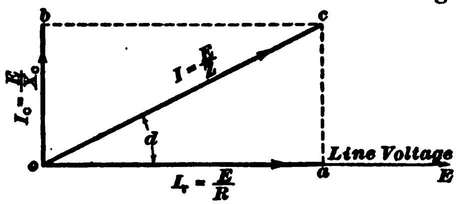


FIG. 16

If this problem is solved by means of the triangle, as explained in Arts. 7 and 8, and the values I_c and X_c are substituted for I_s and X_s, the following relations will be established:

$$I = \sqrt{I_r^2 + I_c^2} \qquad (1)$$

$$\frac{1}{Z} = \sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_c}\right)^2} \qquad (2)$$

10. Inductance and Capacity in Parallel.—Alternating voltages applied to a circuit containing no resistance (an impossible condition), but condensive and inductive reactances only, connected in parallel, as shown in Fig. 17, would establish the currents $I_s = \frac{E}{X_s}$ and $I_c = \frac{E}{X_c}$.

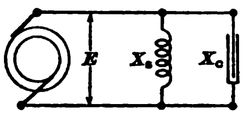


FIG. 17

Inasmuch as I_s would lag 90 time-degrees behind the line voltage and I_c would lead the line voltage by 90 time-degrees, the two currents would be in opposition, as indicated in Fig. 18. The resultant current would be the arithmetical difference between the two components, and it would lead or lag, according to which of the components were the larger. If I_s were the larger, the line current would lag by 90 time-degrees, and if I_c were the larger, the line current would lead by 90 time-degrees.

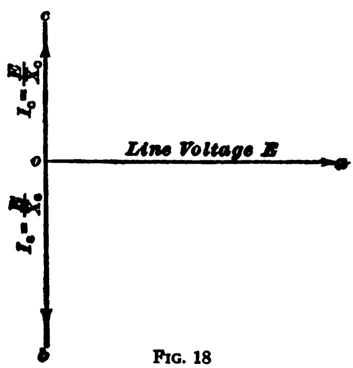


FIG. 18

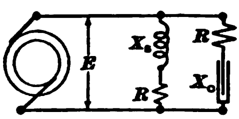


FIG. 19

11. All circuits have resistance, and they may have either, or both, inductance and capacity. The applied voltage may therefore be considered as split into two components, one overcoming resistance and the other actual reactance. Each parallel branch of the circuit shown in Fig. 17 has resistance, and the circuit may be represented as in Fig. 19, in which one branch has resistance R and inductance X_s in series (Art. **1**) and the other has resistance R and capacity X_c, in series (Art. **3**). If the condensive reactance X_c equals the inductive reactance X_s and if both X_c and X_s are large compared with the two resistances R, also assumed equal, the conditions in these two branches will be as represented in the diagrams shown in Figs. 20 and 21, which are similar to Figs. 2 and 5. In the inductive circuit, Fig. 20, the resistive drop U is in phase with the line current, the inductive drop U_s is 90° ahead of the line current, and their vector sum, representing the line voltage, leads the line current, or the current lags, by an angle ϕ, which depends on the relative values of U and U_s. In the condensive circuit, Fig. 21, the line current is found to lead the voltage by an angle ϕ, depending on the relative values of U and U_c.

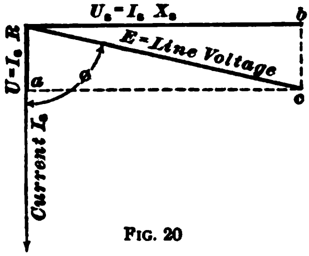


FIG. 20

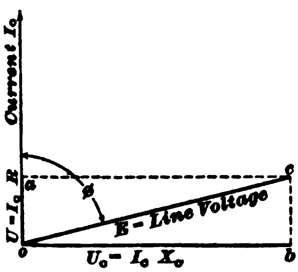


FIG. 21

The current diagram for the complete circuit, Fig. 19, therefore appears as in Fig. 22. Vector I_s, representing current in the inductive circuit, lags behind the voltage vector by the angle ϕ; vector I_c, representing current in the condensive circuit, leads the voltage vector by the angle ϕ_1; and their sum, vector I,

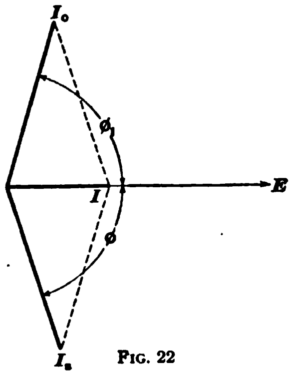


FIG. 22

representing line current, is in phase with the voltage, a condition that prevails only when $X_c = X_s$. The line current I is in this case less than either of its components I_s or I_c.

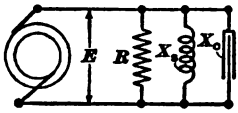


Fig. 23

12. Resistance, Inductance, and Capacity in Parallel.—An alternating voltage applied to a circuit containing resistance and inductive and condensive reactances connected in parallel, as shown in Fig. 23, establishes the currents I_r, I_s, and I_c through the corresponding branches. The line current I is equal to the vectorial sum of these currents, determined as shown in Fig. 24, in which the vector $o\,a$ represents the current I_r, in phase with the line voltage E; vectors $o\,b$ and $o\,c$ represent the currents I_s and I_c; and the resultant vector $o\,e$, represents the line current I. This resultant can be determined graphically as shown by either of the two methods, similar to those described in Art. **5**, or it can be calculated by the following formulas:

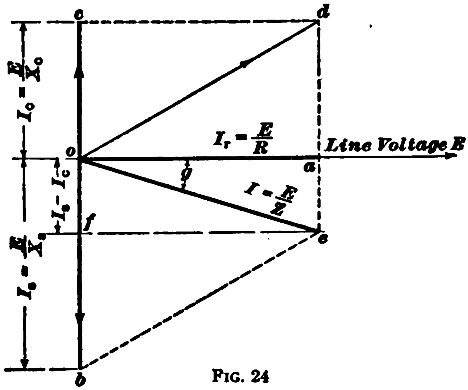


Fig. 24

$$I = \sqrt{I_r^2 + (I_s - I_c)^2} \qquad (1)$$

$$I = \sqrt{I_r^2 + (I_c - I_s)^2}, \qquad (2)$$

depending on whether I_s or I_c is the greater.

Likewise, admittance may be determined from formulas·

$$\frac{1}{Z} = \sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_s} - \frac{1}{X_c}\right)^2} \qquad (3)$$

$$\frac{1}{Z} = \sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_c} - \frac{1}{X_s}\right)^2}, \qquad (4)$$

depending on whether $\frac{I}{X_s}$ or $\frac{I}{X_c}$ is the greater. The impedance can be determined by taking the reciprocal of the admittance or by dividing the line voltage by the line current.

EXAMPLE.—A resistance of 30 ohms, an inductive reactance of 37.5 ohms, and a condensive reactance of 600 ohms are connected in parallel to a 480-volt circuit. Determine: (*a*) the currents through each branch; (*b*) the line current; and (*c*) the impedance of the circuit.

SOLUTION.—(*a*) The current through the resistance

$$I_r = \frac{480}{30} = 16 \text{ amp.} \quad \text{Ans.}$$

The current through the inductive path

$$I_s = \frac{480}{37.5} = 12.8 \text{ amp.} \quad \text{Ans.}$$

The current through the condenser

$$I_c = \frac{480}{600} = .8 \text{ amp.} \quad \text{Ans.}$$

(*b*) The line current, according to formula **1**, is

$$I = \sqrt{16^2 + (12.8 - .8)^2} = 20 \text{ amp.} \quad \text{Ans.}$$

(*c*) The impedance can be determined by the general formula

$$Z = \frac{480}{20} = 24 \text{ ohms.} \quad \text{Ans.}$$

Also, it can be determined, without first determining the line current, by formula **3**. Thus,

$$\frac{1}{Z} = \sqrt{\left(\frac{1}{30}\right)^2 + \left(\frac{1}{37.5} - \frac{1}{600}\right)^2} = \sqrt{\left(\frac{1}{30}\right)^2 + \left(\frac{1}{40}\right)^2} = \frac{1}{24} \text{ mho}$$

If $\frac{1}{Z} = \frac{1}{24}$, $Z = 24$ ohms. Ans.

EXAMPLES FOR PRACTICE

1. A choke coil, a condenser, and a non-inductive resistance are connected in series. The inductive reactance is 32 ohms, the condensive reactance 160 ohms, and the resistance 240 ohms. Find the impedance of the circuit. Ans. 272 ohms

2. If the choke coil, condenser, and resistance described in example 1 were connected in parallel, what would be the impedance of the circuit?
Ans. 39.5 ohms

3. A non-inductive resistance of 15 ohms and an inductive reactance of 8 ohms, are connected in parallel across a 120-volt circuit. What is the value of the main current?
Ans. 17 amp.

POWER IN TWO-WIRE CIRCUITS

THEORETICAL CONSIDERATIONS

13. Power in Non-Inductive Circuits.—In an alternating-current circuit, the power at any instant is equal to the product of the voltage and the current values at that

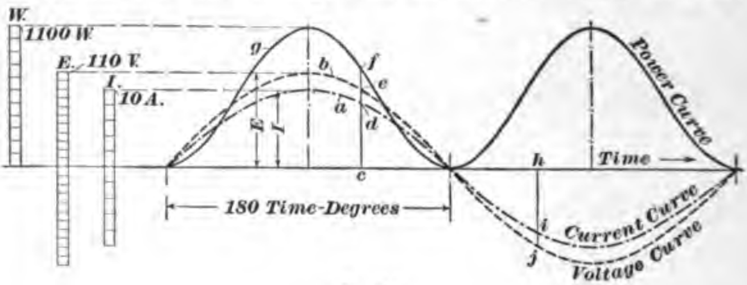


FIG. 25

instant. For example, let Fig. 25 represent the condition of an alternating-current, non-inductive circuit. The current represented by the curve *a* has the maximum value *I*, assumed to be 10 amperes, and is in phase with the voltage, curve *b*, of the maximum value *E*, assumed to be 110 volts. Since maximum amperes and maximum volts occur simultaneously, the maximum power is $10 \times 110 = 1,100$ watts, as shown by the curve *g* and the scale *W*. The power at any other instant, such as *c*, is likewise equal to the product of the instantaneous ordinates *c d* and *c e*. The values of these ordinates can be determined by any convenient scales, as *I* and *E*, and the value of their product by the power scale *W*, giving an ordinate *c f* of the power curve. Other points on this curve are established in the same way, and the complete curve indicates the rate at which energy is supplied to the circuit.

14. Positive and Negative Work and Power. Under the conditions assumed for Fig. 25, the simultaneous ordinates of the voltage and the current curves, for example, *c e* and *c d* or *h j* and *h i* are always of the same sign, both positive or both negative. Their product must therefore be positive, making the power curve appear wholly above the zero axis. In reality, energy is neither positive nor negative, nor does it have direction. It may be considered as positive or negative, however, according to whether it is supplied from a source to a system or returned from the system to the source. For example, the conditions represented in Fig. 25 show continuous energy flow, at the rate represented by the curve *g*, from the alternator to its load. No energy is reacted from

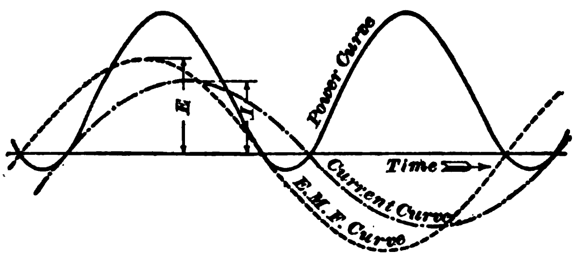


FIG. 26

the system to the alternator, and all the energy may be considered as positive.

15. Power in Reactive Circuits.—Alternating voltage in a circuit having inductance or capacity overcomes both reactance and resistance and establishes a current in consuming devices, such as lamps and motors. Some of the energy from the alternator is required to overcome the reactance, some is converted into heat in the resistance, and the remainder is converted into heat, light, work, or other forms of energy in the consuming devices. The energy that overcomes the reactance is returned to the source as electric energy; therefore, this part of the total energy may be considered as negative.

Fig. 26 serves to illustrate the conditions in an alternating-current circuit in which the current lags less than 90 time-degrees behind the voltage. Points on the power curve are

found as explained in Art. **13**, by multiplying together simultaneous ordinates of the current and voltage curves.

When one of the simultaneous ordinates is positive and the other negative, their product is negative, as represented by the loops of the power curve below the horizontal axis. These negative loops represent the rate at which the energy is returned from the circuit to the source.

16. Wattless Current.—Current in a circuit representing no corresponding work is called *wattless current*. In Fig. 27, this condition in an alternating-current circuit is represented when the angle of lag is 90 time-degrees. In this case, the power curve lies as much above as below the axis, indicating that the circuit receives and returns energy at the same rate. The energy actually expended is zero, although a current

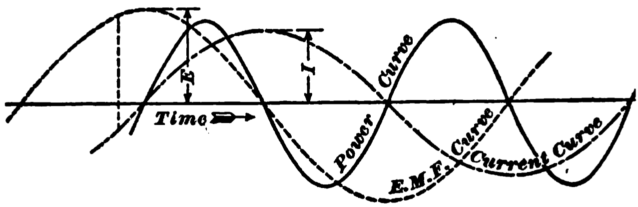


FIG. 27

exists in the circuit. Such a condition would exist if an alternator were supplying current to a device having no resistance, but inductance only; that is, all the current would be wattless, or idle, because no work would be done by it.

If alternating voltage acted in condensive circuits without resistance, the current would lead the voltage by 90 time-degrees and would be wattless; such wattless current is called *charging current*. In every circuit containing inductance or capacity, unless the two balance each other, some of the current is wattless.

CALCULATION OF POWER

17. Current and Voltage in Phase.—When the current and the voltage are in phase, as is the case in continuous-current circuits and in non-reactive single-phase alternating-

current circuits, the power is equal to the product of the current and the voltage, as indicated by the ammeter and voltmeter.

This may be expressed in the form of a formula; thus,

$$P = E\ I$$

in which P = power, in watts;
E = voltage;
I = current, in amperes.

Example.—A non-inductive load of 550 incandescent lamps, each lamp taking energy at the rate of 40 watts, is connected to a 110-volt circuit. What is the value of the current?

Solution.—When all the lamps are burning, energy will be taken at the rate of $550 \times 40 = 22{,}000$ watts. According to the formula just given, $22{,}000 = 110 \times I$; therefore,

$$I = \frac{22{,}000}{110} = 200 \text{ amp.} \quad \text{Ans.}$$

18. Current and Voltage Out of Phase.—When voltage and current are out of phase, the indication of either the voltmeter or the ammeter may be considered as a resultant value. In a series circuit, the indicated voltage is the resultant of two components, one in phase with the current and the other differing 90 time-degrees from it, or in quadrature with it. In a parallel circuit, the indicated current is the resultant of two components, one in phase with the voltage and the other differing 90 time-degrees from it. As it makes no difference in the final result whether the voltage or the current is resolved, the common practice in all cases is to consider the current as resolved into two components, one in phase with the voltage and the other in quadrature with it. The power of the circuit is the product of the voltage and the component of the current in phase with it.

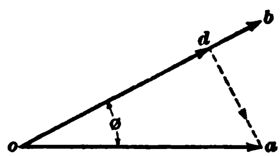


Fig. 28

For example, let vector *o b*, Fig. 28, represent the indicated voltage E of a circuit and vector *o a* the indicated current I, the phase difference being an angle ϕ. Vector *o a* can be resolved into two components, namely, *o d* in phase with the voltage and *d a* perpendicular to it. The power is equal to

the product of vector $o\,b$ and component $o\,d$. But $\frac{o\,d}{o\,a} = \cos\phi$, and $o\,d = o\,a \cos\phi$; therefore, $o\,b \times o\,d = o\,b \times o\,a \cos\phi$, or the watts,

$$P = E\,I \cos\phi$$

The product $E\,I$ is sometimes called the ***volt-amperes***, or ***apparent watts***, while $E\,I \cos\phi$, or P, is the ***true power***, or the ***real watts***, usually expressed simply as ***watts***. This formula is applicable to all single-phase circuits.

19. Power Factors.—The factor, $\cos\phi$, by which the product of the volts and amperes must be multiplied to give the watts, is called the *power factor* of the circuit. This factor must be known before the power can be determined from the indications of a voltmeter and an ammeter. An instrument called the *power-factor meter* indicates the power factor, or it can be calculated from the readings of a wattmeter, a voltmeter, and an ammeter, using the formula of Art. **18**. The wattmeter gives the true power $EI \cos\phi$, and from the formula referred to

$$\cos\phi = \frac{P}{I\,E} = \frac{\text{real watts}}{\text{apparent watts}}$$

If either the power factor or the angle of phase difference is known, the other can be found by referring to Table I. These power factors are the natural cosines of the angles, and are practically the same values as given in a preceding Section.

EXAMPLE 1.—A motor on test develops an output of 10 horsepower with an input of 50 amperes from a 220-volt circuit. If the motor output, in watts, is 80 per cent. of the input: (*a*) what is the power factor? (*b*) what is the angle of phase difference?

SOLUTION.—(*a*) As 1 H. P. = 746 watts, the output of 10 H. P. is $746 \times 10 = 7{,}460$ watts. Since this is 80 per cent., or .8, of the input, the input must be $7{,}460 \div .8 = 9{,}325$ real watts. The volt amperes, or apparent watts, are, however, $220 \times 50 = 11{,}000$. According to the formula, the power factor

$$\cos\phi = \frac{9{,}325}{11{,}000} = .848 \quad \text{Ans.}$$

TABLE I

POWER FACTORS

Phase Difference ϕ Time-Degrees	Power Factor $\cos\phi$	Phase Difference ϕ Time-Degrees	Power Factor $\cos\phi$	Phase Difference ϕ Time-Degrees	Power Factor $\cos\phi$
0	1.0000	31	.857	61	.485
1	.9998	32	.848	62	.469
2	.9994	33	.839	63	.454
3	.9986	34	.829	64	.438
4	.9976	35	.819	65	.423
5	.996	36	.809	66	.407
6	.995	37	.799	67	.391
7	.993	38	.788	68	.375
8	.990	39	.777	69	.358
9	.988	40	.766	70	.342
10	.985	41	.755	71	.326
11	.982	42	.743	72	.309
12	.978	43	.731	73	.292
13	.974	44	.719	74	.276
14	.970	45	.707	75	.259
15	.966	46	.695	76	.242
16	.961	47	.682	77	.225
17	.956	48	.669	78	.208
18	.951	49	.656	79	.191
19	.946	50	.643	80	.174
20	.940	51	.629	81	.156
21	.934	52	.616	82	.139
22	.927	53	.602	83	.122
23	.921	54	.588	84	.105
24	.914	55	.574	85	.087
25	.906	56	.559	86	.070
26	.899	57	.545	87	.052
27	.891	58	.530	88	.035
28	.883	59	.515	89	.017
29	.875	60	.500	90	.000
30	.866				

(*b*) The table of power factors shows that the phase difference corresponding to a power factor of .848 is 32 time-degrees, or the angle of lag is 32°. Ans.

EXAMPLE 2.—Electrical energy is to be supplied at the rate of 165 kilowatts to a load having a power factor of .8. The voltage of the circuit is 2,200. What is the current?

SOLUTION.—According to the formula, $.8=\frac{165{,}000}{\text{apparent watts}}$; therefore, apparent watts, $I\,E=\frac{165{,}000}{.8}=206{,}250$. But $E=2{,}200$; therefore,

$$I=\frac{206{,}250}{2{,}200}=93.8 \text{ amp. Ans.}$$

20. Power factors ranging from .75 to 1 are common in practice; lower power factors, down to .5, are sometimes encountered, but anything lower than .5 is very rare. Low power factors are undesirable, because the lower the power factor the greater is the wattless component of the current. This wattless current adds to the heat of the circuit and thereby reduces its ability to carry power current; in fact, the useful capacity of alternators and lines may be often increased by connecting with the circuits devices that correct the power factor or bring it nearer unity.

Synchronous motors can be made to perform this function, and when so used they are known as *synchronous condensers*. In large systems, where many induction motors are operating, synchronous motors are frequently employed to perform the double duty of driving some continuously operating machine, as pumps or blowers, and simultaneously improving the power factor of the circuit. This subject will be treated in another Section.

EXAMPLES FOR PRACTICE

1. A non-inductive heating device having a resistance of 27.5 ohms is connected to a 110-volt alternating-current circuit. Find the value of the power. Ans. 440 watts

2. If the cost of 1 kilowatt-hour of electrical energy is 10 cents, what will be the cost of operation for 5 hours of the heating device described in example 1? Ans. 22c.

3. A carbon-filament incandescent lamp connected to a 110-volt alternating-current circuit has a current of .5 ampere passing through it. Find the energy consumed in 1,000 hours. Ans. 55 K.-W.-hr.

4. A line voltage is 220 and a line current 50 amperes. If there is a phase displacement of 30 electrical time-degrees between the voltage and the current, what is the power? Ans. 9,526 watts

POLYPHASE CIRCUITS

FUNDAMENTAL PRINCIPLES

21. Generation of Polyphase Currents.—Let *a* and *b*, Fig. 29 (*a*), represent two conductors fixed 90 space-degrees from each other on an armature that rotates between the poles of a two-pole magnet. The phase difference between the voltages induced in the two conductors is 90 time-degrees at every instant. For example, when the conductor *a* passes parallel to the lines of force, *b* passes at right angles to them; consequently, when the induced voltage in *a* is zero, that in *b* is maximum.

The variations of these voltages are shown in Fig. 29 (*b*), in which the variations in the conductor *a* are represented by the curve *a* and those in the conductor *b*, by the curve *b*. If two external circuits are connected to the ends of the conductors *a* and *b*, the voltages in these circuits differ in phase 90 time-degrees, thus forming a *two-phase*, or *quarter-phase system*. All circuits that are a combination of two or more phases are also known as **polyphase circuits**, and the currents in such circuits are called *polyphase currents*. Fig. 29 shows the elements of a *two-phase generator*.

22. In conductors *a*, *b*, and *c*, Fig. 30 (*a*), fixed on the armature 120 space-degrees from each other, and revolved between the poles of a two-pole magnet, are established electromotive forces differing in phase by 120 time-degrees. When the conductor *a* is in position *o*, the conductors *b* and *c* are at the positions *8* and *16*, respectively; consequently, when the

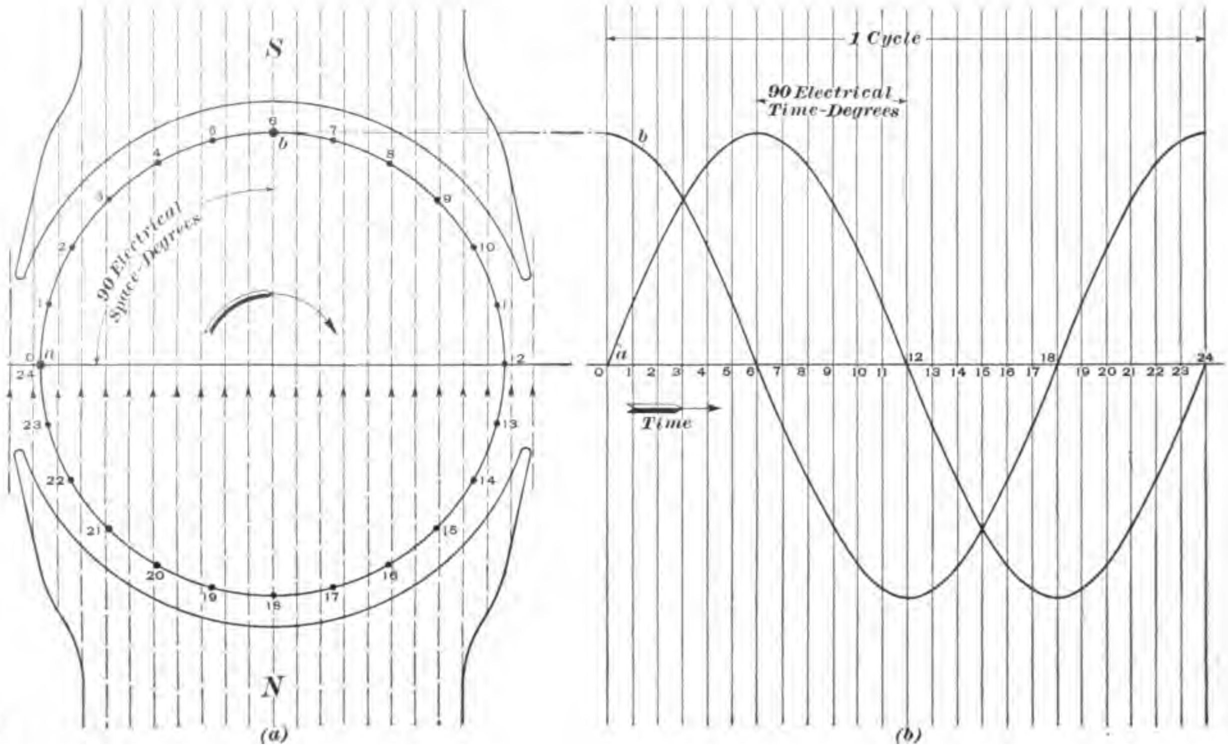

S
N
90 Electrical Space-Degrees
1 Cycle
90 Electrical Time-Degrees
Time
(a)
(b)

FIG. 29

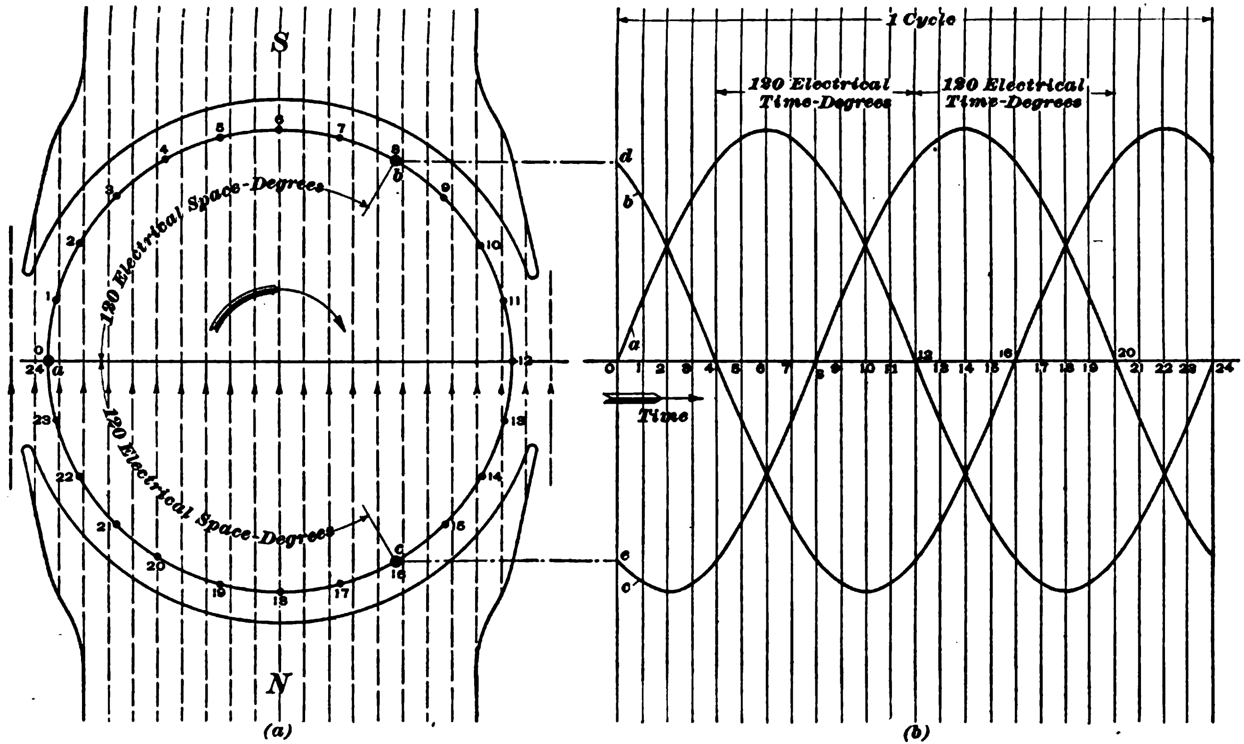

S
N
120 Electrical Space-Degrees
120 Electrical Space-Degrees
a
b
c
d
e
1 Cycle
120 Electrical Time-Degrees
120 Electrical Time-Degrees
Time
(a)
(b)

Fig. 30

induced voltage in a is zero, that in b and c will be of the value represented by the ordinates $0\text{–}d$ and $0\text{–}e$, Fig. 30 (b), in which the curves a, b, and c represent the variation of the voltages in the conductors a, b, and c, respectively.

If three external circuits are connected to the ends of the conductors a, b, and c, the voltages in these circuits will differ in phase 120 time-degrees, thus forming a *three-phase system*, and the figure will represent elements of a *three-phase generator*.

23. System of Notation.—In the succeeding discussion, the system of subscripts used with the symbols representing current and voltage relations in polyphase circuits is chosen to indicate direction. Junction points in circuits, as a and b, Fig. 31, are lettered, and these letters, used as subscripts, are written in such order as to denote that the direction of the current or voltage is from the junction marked with a first subscript toward the junction marked with a second subscript. For example, the current I_{ab} is the current from a to b, and E_{ab} is the voltage establishing this current. The current I_{ba} is from b to a, and the voltage E_{ba} is the voltage establishing this current.

FIG. 31

The current I_{ab}, being exactly opposite in direction to the current I_{ba}, differs in phase from it by 180 time-degrees. If the current I_{ba} is reversed, it becomes $-I_{ba}$ and its direction is the same as that of I_{ab}; hence, $-I_{ba} = I_{ab}$. Likewise, $-I_{ab} = I_{ba}$. The order in which the subscripts are taken from the diagram must be observed carefully, as a change in their order will change the position of the vector representing that current or voltage by 180 time-degrees. If the circuit is nonreactive, I_{ab} and E_{ab} or I_{ba} and E_{ba} are in phase; otherwise, there is an angle of lag or lead, the value of which depends on the relative proportion of the resistance and the reactance and on whether the reactance is inductive or condensive.

24. Kirchhoff's First Law.—*As much current is directed toward any junction as away from it.* For example, if the current toward the junction d, Fig. 32, is I_{cd} and the currents away from the junction are I_{da} and I_{db}, then

$$I_{cd} = I_{da} + I_{db}$$

When the currents in the branches are in phase, this equation can be solved algebraically. In most cases, however, the currents differ in phase, and then the solution must be vectorial, since algebraic solution would give wrong results. The equation then indicates the operation that must be performed with the vectors of the currents represented by the symbols in the equation. The vectorial equations may be subjected to all operations possible with any algebraic equation, but the final solution must be graphical, proper consideration being given to the phase differences. For example, in the preceding equation the terms I_{da} and I_{db} of the right member, may be transferred to the left member, provided their signs are changed; the equation then becomes

$$I_{cd} - I_{da} - I_{db} = 0$$

For the factors $-I_{da}$ and $-I_{db}$ may be substituted, their equivalents I_{ad} and I_{bd}, and the equation becomes

$$I_{cd} + I_{ad} + I_{bd} = 0$$

This equation serves as a basis for the modified form of Kirchhoff's first law as used in solutions of problems involving alternating currents.

Modified First Law.—*The sum of currents directed toward any junction is zero.*

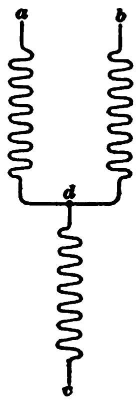


FIG. 32

25. Kirchhoff's Second Law.—*In any closed electric circuit, the combined opposing voltages are equal to the combined applied voltages acting in that circuit.* A clear understanding of the term *opposing voltage* is extremely necessary. Thus, the opposing voltage caused by inductive reactance is the counter electromotive force of self-induction, not the applied voltage necessary to overcome it. The opposing voltage is equal in value to the applied voltage, but differs from it by 180 time-degrees. The opposing voltage lags behind the current 90 time-degrees, while the applied voltage leads the current by the same angle. Similarly, the opposing voltage caused by condensive reactance is the counter electromotive force equal in value to the applied voltage, but in exact opposition to it;

the opposing voltage leads the current by 90 time-degrees, in this case, while the applied voltage lags behind the current by the same angle.

There is no counter electromotive force in case of resistance, the applied voltage being usually considered as consumed by the resistance. For the purpose of Kirchhoff's law, however, it is necessary to assume that the applied voltage instead of being consumed is opposed or counterbalanced by another voltage, the applied voltage being in phase with the current and the opposing voltage in exact opposition.

26. When all applied voltages acting in a like direction around the circuit are denoted by a plus sign, and all opposing voltages by a minus sign, Kirchhoff's second law is usually stated thus: *The algebraic sum of all voltages in any closed circuit is zero.* The assumed direction around the circuit is usually referred to as a *positive direction.* It is immaterial whether the positive direction corresponds to the actual direction of the current or not. For example, suppose that the actual direction of the current in the circuit $a\,b\,c\,d$, Fig. 33, is as indicated by arrowheads on the lines. The applied voltage in the generator establishing this current is E_{da}, and the opposing voltages are E_{cb} and E_{dc}. The resistance of connecting wire $a\,b$ is assumed to be negligible. If the positive direction is assumed to be the same as the direction of current and signs are given to all voltages accordingly, then

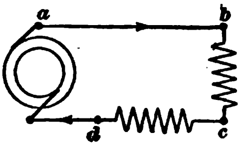


FIG. 33

$$E_{da}-E_{cb}-E_{dc}=0;\text{ or, } E_{da}=E_{cb}+E_{dc}$$

Suppose that the positive direction is taken as exactly opposite the direction of current; then,

$$-E_{da}+E_{cb}+E_{dc}=0;\text{ or, } E_{da}=E_{cb}+E_{dc},$$

as before. In the first equation, instead of the factors $-E_{cb}$ and $-E_{dc}$, their equivalents E_{bc} and E_{cd} may be substituted, and the equation becomes

$$E_{da}+E_{bc}+E_{cd}=0$$

In the second equation, the factor E_{ad} may be substituted for its equivalent $-E_{da}$, and the equation becomes

$$E_{ad}+E_{cb}+E_{dc}=0$$

These two equations serve as a basis for the modified form of Kirchhoff's second law as used with vectorial equations in alternating-current problems.

Modified Second Law.—*The vectorial sum of voltages taken completely around any circuit, with their directions assumed either all clockwise or all counter-clockwise, is equal to zero.*

27. It should be clearly understood that the equations written in accordance with Kirchhoff's laws indicate operations on vectors; that is, the factors in the equation indicate whether the vectors they represent are to be added or subtracted to obtain the resultant. In no case should the numerical values of voltages or currents represented by these vectors be substituted in the equation, as the results would then be erroneous. The numerical value indicates the magnitude only; both magnitude and phase relation must be considered in combining alternating currents or voltages.

28. It should be remembered also, that if the connections of any coil to the line are reversed, or the direction of the current in the coil is reversed, the vector representing the electromotive force or the current of that coil is likewise reversed, or its phase relation changed 180 time-degrees.

TWO-PHASE CIRCUITS

29. Two-Phase, Four-Wire Circuits.—The simplest two-phase circuit is a four-wire system, such as is shown diagrammatically in Fig. 34. It consists of two single-phase circuits, each of which is loaded independently of the other. Here, line voltage equals phase voltage and line current equals phase current. Care is usually taken to load the phases as equally as possible in order to have like values of current in the windings of the alternator. If the loads are equal, the system is said to be *balanced*.

The voltage and current calculations are carried out separately for each phase, in the same way as for single-phase circuits. The total power of the two-phase, four-wire system is the sum of the powers in the separate phases.

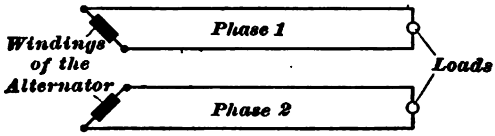


FIG. 34

30. Two-Phase, Three-Wire Circuits.—In the case of a perfectly balanced load on a two-phase system, some economy in copper and insulators may be made by combining one conductor of phase *1* and one of phase *2*, Fig. 34, into one single conductor, usually called the *return*, or *neutral*, *conductor*. This system, known as a *two-phase, three-wire system*, is shown in Fig. 35, in which A represents the return conductor.

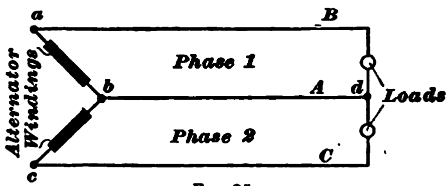


FIG. 35

The voltage and current relations in two-phase, three-wire circuits are determined as follows: According to Kirchhoff's first law,

$$I_{ab}+I_{cb}+I_{db}=0$$

The currents I_{ab} and I_{cb} are established by voltages E_{ab} and E_{cb} of phases *1* and *2*, respectively; these currents, therefore, differ in phase by 90 time-degrees. In a balanced system, these currents are equal and can be represented by equal vectors, as in Fig. 36, in which I_{cb} is assumed to be in the lead. Assume also that the voltage in each phase leads the current by 30 time-degrees; then the voltages can be represented by the vectors E_{ab} and E_{cb}.

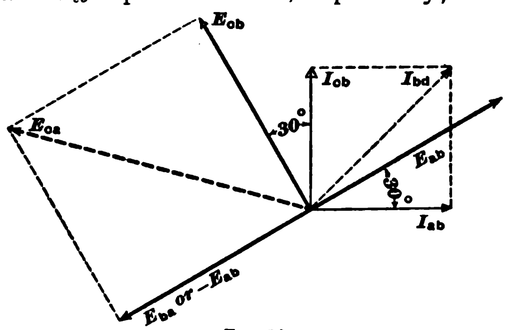


FIG. 36

The currents in the wires B and C, Fig. 35, must be of the same values as the phase currents I_{ab} and I_{cb}; the current in the neutral wire A is $-I_{db}$, or I_{bd}, and

$$I_{bd}=I_{ab}+I_{cb}.$$

This equation indicates that the vector I_{bd}, representing the current in wire A, is the vectorial sum of I_{ab} and I_{cb}, or the diagonal of the square of which the two latter vectors form two sides, as shown in Fig. 36.

31. According to Kirchhoff's second law, the equation of voltages across the pairs of conductors, Fig. 35, is $E_{ca}+E_{ab}+E_{bc}=0$; therefore,

$$E_{ca}=-E_{ab}-E_{bc}=E_{ba}+E_{cb}$$

In other words, the voltage across the two outer conductors is the vectorial sum of the equal voltages across the two phases. In order to find this sum, the two vectors E_{ba} and E_{cb} must be drawn in the direction indicated by the subscripts, the direction of E_{ba}, or $-E_{ab}$, being opposite the direction of E_{ab}.

Fig. 36, therefore, shows the relative values and phase relations of all the currents and voltages in a balanced two-phase, three-wire system in which the current in each phase lags 30 time-degrees behind its voltage. The vector E_{ca} is the diagonal of a square of which vectors representing the phase voltages form two sides. Since the diagonal of a square is $\sqrt{2}$, or 1.414, times a side, the following statements are true of a balanced two-phase three-wire system:

1. The voltage across outside wires$=1.414\times$phase voltage.
2. The current in a neutral wire$=1.414\times$phase current.

EXAMPLE.—In a balanced two-phase, three-wire system, the phase voltage is 440 and the phase current 100 amperes. (*a*) What is the voltage across the outside conductors? (*b*) What is the current in the neutral conductor?

SOLUTION.—(*a*) The voltage across the outside conductors is $1.414\times 440=622$. Ans.

(*b*) The current in the neutral conductor is $1.414\times 100=141.4$ amp. Ans.

32. Two-Phase Interconnected Circuits.—Sometimes the winding of each phase of two-phase devices is in two parts

interconnected as in either Fig. 37 or Fig. 38. The first is known as the *star connection* and the second as the *mesh connection*, both of which terms are more commonly used with three-phase systems, as is explained later. The windings marked *I* belong to one phase and those marked *II* to the other.

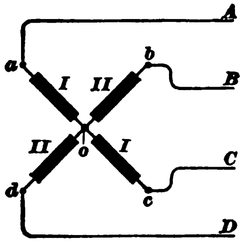


FIG. 37

33. With star connection, Fig. 37, the voltages between the terminals *a o*, *b o*, *c o*, and *d o* are each equal to one-half the phase voltage. The currents in the lines *A*, *B*, *C*, and *D* are each equal to the current in its part of the winding *a o*, *b o*, *c o*, and *d o*, and, according to Kirchhoff's first law,

$$I_{ao}+I_{bo}+I_{co}+I_{do}=0$$

If these currents are assumed to be equal (balanced system), their vectors will be as shown in Fig. 39. If the current lags behind the voltage in each winding by an angle *a*, the voltage vectors also can be drawn as shown.

The voltage across the wires *A* and *C* or *B* and *D*, Fig. 37, is the phase voltage. The voltage across the wires *A* and *B*, *B* and *C*, *C* and *D*, or *D* and *A* is found according to Kirchhoff's second law. For example, to find the voltage across *A* and *B*, $E_{ab}+E_{bo}+E_{oa}=0$; therefore,

$$E_{ab}=-E_{bo}-E_{oa}=E_{ob}+E_{ao}$$

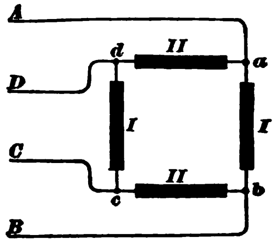


FIG. 38

The vector representing this voltage E_{ab} is shown dotted in Fig. 39. Each vector E_{ao} and E_{ob} represents one-half the phase voltage; therefore, the voltage

$$E_{ab}=\frac{E}{2}\times 1.414=.707\ E,$$

in which *E* is the phase voltage.

Similarly, the voltage across any other combination can be found.

EXAMPLE.—If the voltage between the conductors A and C, Fig. 37, is 220, what is the voltage between conductors A and B?

SOLUTION.—The voltage between A and C is the phase voltage; therefore, according to the preceding formula, the voltage between A and B is $E_{ab} = .707 \times 220 = 155.5$. Ans.

34. For the mesh connection, Fig. 38, Kirchhoff's second law gives the equation

$$E_{da} + E_{ab} + E_{bc} + E_{cd} = 0,$$

and these voltages, being equal, can be represented by vectors lettered accordingly, as in Fig. 40. The voltages across the

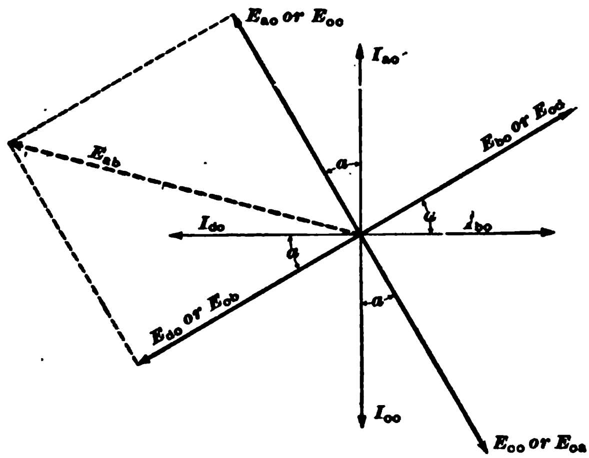


FIG. 39

terminals $a\,b$, $b\,c$, $c\,d$, and $d\,a$, Fig. 38, are each equal to one-half the phase voltage E, and the voltage across the terminals $a\,c$ and $d\,b$ can be found by writing the vectorial equations according to Kirchhoff's second law; thus,

$$E_{ac} + E_{cd} + E_{da} = 0; \text{ or, } E_{ac} = -E_{cd} - E_{da} = E_{dc} + E_{ad}$$

From this equation, the vector E_{ac}, Fig. 40, is drawn. E_{ac} being the diagonal of a square of which E_{dc} and E_{ad}, each equal to $\frac{E}{2}$, form two sides, the voltage across terminals $a\,c$ or $d\,b$, Fig. 38, equals $\frac{1.414\,E}{2} = .707\,E$.

The currents in conductors A, B, C, and D, Fig. 38, are determined by means of Kirchhoff's first law; thus,

$$I_{Aa}+I_{da}+I_{ba}=0;\text{ or, }I_{Aa}=I_{ad}+I_{ab}$$

If it is assumed that the current in each winding lags behind its voltage by an angle a, the vectorial representation will be

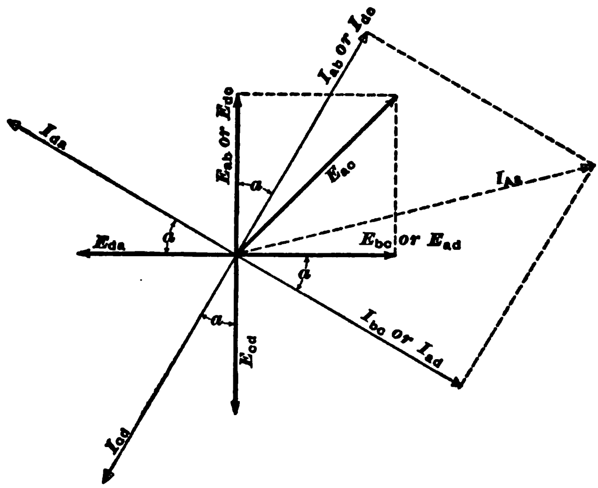


FIG. 40

as shown in Fig. 40. The current in conductor A, according to the foregoing equation, is represented by the vector I_{Aa}, which is the diagonal of a square having I_{ad} and I_{ab} for two sides. Similarly, the current in any other conductor can be determined.

Let I = current in any one of the four parts of the winding;
I_e = current in any line conductor.

Then, $$I_e=1.414\ I$$

EXAMPLE.—If the current in a line conductor of a two-phase interconnected (mesh) system is 283 amperes, what is the current in the windings?

SOLUTION.—According to the preceding formula, $283=1.414\ I$. Therefore, $I=283\div1.414=200$ amp. Ans.

THREE-PHASE CIRCUITS

35. Three-Phase Star Connection.—Joining an end of each phase of a three-phase winding in a common point, called a *neutral point*, as at o, Fig. 41, forms a *three-phase star connection*. The voltage across any phase, as E_{oa}, E_{ob}, or E_{oc}, is the *phase voltage*, and the voltage between any two line wires, as E_{ab}, E_{bc}, or E_{ca}, is the *line voltage*. If the system is balanced, the three line voltages are equal.

According to Kirchhoff's second law,

$$E_{ab}+E_{bo}+E_{oa}=0;\text{ or, }E_{ab}=E_{ao}+E_{ob} \qquad (1)$$
$$E_{bc}+E_{co}+E_{ob}=0;\text{ or, }E_{bc}=E_{bo}+E_{oc} \qquad (2)$$
$$E_{ca}+E_{ao}+E_{oc}=0;\text{ or, }E_{ca}=E_{co}+E_{oa} \qquad (3)$$

Each line wire is in series with a phase of the winding; therefore,

line current = phase current

According to Kirchhoff's first law, the sum of the currents directed from the neutral point of a three-phase star-connected system equals zero, or, in Fig. 41,

$$I_{oa}+I_{ob}+I_{oc}=0$$

These three currents can be represented vectorially as in Fig. 42, and the three phase voltages E_{oa}, E_{ob}, and E_{oc} also can be represented by vectors showing the proper angle of lag a. This angle may have any value according to the conditions of the circuit.

If the three vectors of the phase voltages are given, the vectors of the three line voltages can be drawn according to equations **1**, **2**, and **3**, but it must be remembered that E_{ao} is the reverse of E_{oa}, E_{bo} the reverse of E_{ob}, and E_{co} the reverse of E_{oc}.

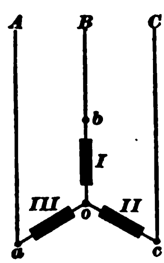


FIG. 41

36. In a three-phase star connection, a phase difference of 30 time-degrees always exists between the line and phase voltages, as noted between the vectors E_{ab} and E_{ob}, Fig. 42. Since E_{ab} is the diagonal of a parallelogram, a perpendicular dropped from the extremity of the vector E_{ob} bisects the

vector E_{ab}. Then, $\frac{\frac{1}{2} E_{ab}}{E_{ob}} = \cos 30°$, $\frac{1}{2} E_{ab} = E_{ob} \cos 30°$, and $E_{ab} = 2 E_{ob} \cos 30°$. In Table I, cos 30° is found to be .866; therefore,

$$E_{ab} = 2 \times .866\ E_{ob} = 1.732\ E_{ob};$$

or, *line voltage = 1.732 × phase voltage*

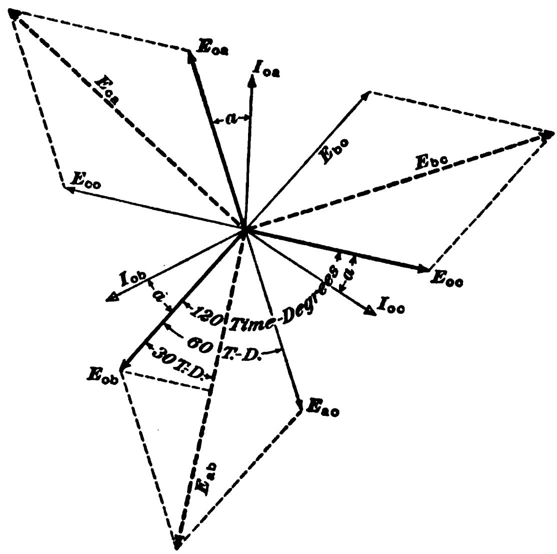


FIG. 42

EXAMPLE 1.—If the voltage across a phase is 6,350, what is the line voltage with phases connected in star?

SOLUTION.—According to the formula just given,
line voltage = 1.732 × 6,350 = 11,000, approx. Ans.

EXAMPLE 2.—The line voltage is 6,600. What is the phase voltage, or the voltage between any of the line wires and the neutral point?

SOLUTION.—According to the formula, 6,600 = 1.732 × phase voltage; or,
phase voltage = 6,600 ÷ 1.732 = 3,810. Ans.

37. The **three-phase four-wire system,** shown diagrammatically in Fig. 43, is a modification of a star connection. The fourth conductor O is connected to the neutral point and is known as the *neutral conductor.* Motors are connected with

the three main conductors A, B, and C, and lamps are usually connected between each of these conductors and the neutral O. The voltage between any outside conductor and the neutral is the same as the phase voltage; the voltage between any two outside conductors, as A and B, B and C, or C and A, is the same as with a star connection. The line currents are the same as the phase currents. With the same load on all three phases, that is, with the system balanced, the neutral carries no current; otherwise, the current in the neutral wire depends on the extent of unbalancing.

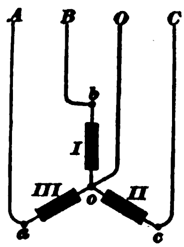


FIG. 43

38. Three-Phase Delta Connection.—Joining the three phases of a three-phase winding end to end, so as to form a closed circuit, as in Fig. 44, is called *mesh* or *delta, connection.* According to Kirchhoff's second law,

$$E_{ab}+E_{bc}+E_{ca}=0$$

The vectors of these voltages and of their corresponding phase currents I_{ab}, I_{bc}, and I_{ca} are shown in Fig. 45, it being assumed that the current lags behind the voltage by an angle a. Fig. 44 shows that the voltage between any two of the line conductors A, B, and C is the voltage of the phase joining the two; that is,

line voltage = phase voltage

The line currents in case of a delta connection are determined according to Kirchhoff's first law; for example,

$$I_{Aa}+I_{ba}+I_{ca}=0;\text{ or, } I_{Aa}=I_{ab}+I_{ac}$$

Similar equations can be written for the line currents I_{Bb} and I_{Cc} and the line-current vectors drawn accordingly, as in Fig. 45.

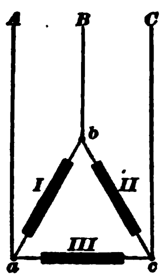


FIG. 44

39. In a three-phase delta connection, a phase difference of 30 time-degrees always exists between the line and phase currents, as indicated between I_{Aa} and I_{ac}, Fig. 45. By the same line of reasoning as followed in Art. **36**, $\frac{1}{2}I_{Aa}=I_{ac}\cos 30°$; $I_{Aa}=2\times I_{ac}\times .866=1.732\,I_{ac}$, or

line current = 1.732 × phase current

EXAMPLE.—The line current to a delta-connected device is 3,464 amperes. What is the current per phase, or the phase current?

SOLUTION.—According to the formula just given,

$$3,464 \div 1.732 = 2,000 \text{ amp. Ans.}$$

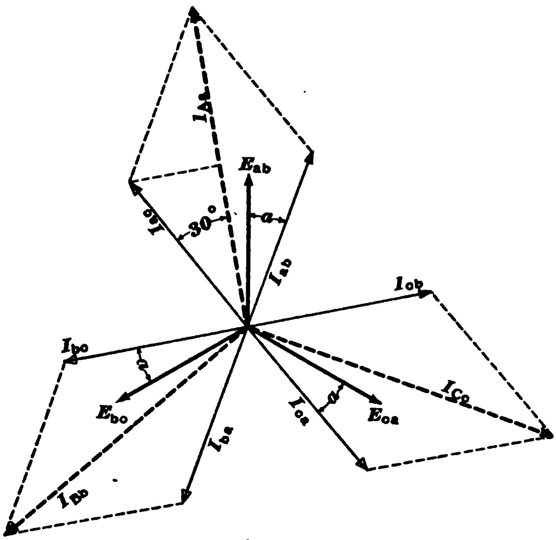


FIG. 45

40. A feature of importance in connection with the study of electrical measuring instruments should be noted from Fig. 45. At unity power factor, the phase-voltage and phase-current vectors would coincide; that is, vector E_{ab} would coincide with vector I_{ab}, E_{bc} with I_{bc}, and E_{ca} with I_{ca}. Line current vector I_{Cc} would then be at right angles to the phase-voltage vector E_{ab}, indicating that the current and the voltage represented by these vectors differ in phase by 90 time-degrees.

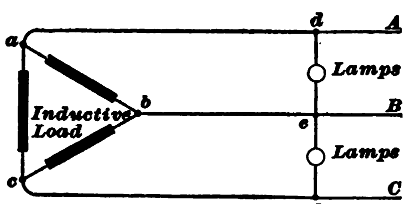


FIG. 46

41. Three-Phase Unbalanced Loads.—A vector diagram may be employed in solving a problem in which an unbalanced load on a three-phase system is involved. For example, a delta-connected inductive load,

Fig. 46, is supplied from a three-phase, 440-volt circuit. The phase current is 150 amperes, and the power factor of the load, .866. In addition to this, two non-inductive loads of incandescent lamps, with the current per load of 100 amperes at unity power factor, are connected on two of the phases, thus unbalancing the circuit.

The inductive load being alike on each phase, the voltages E_{ab}, E_{bc}, and E_{ca} across the corresponding phases are uniform. In Fig. 47, these voltages are represented by three vectors

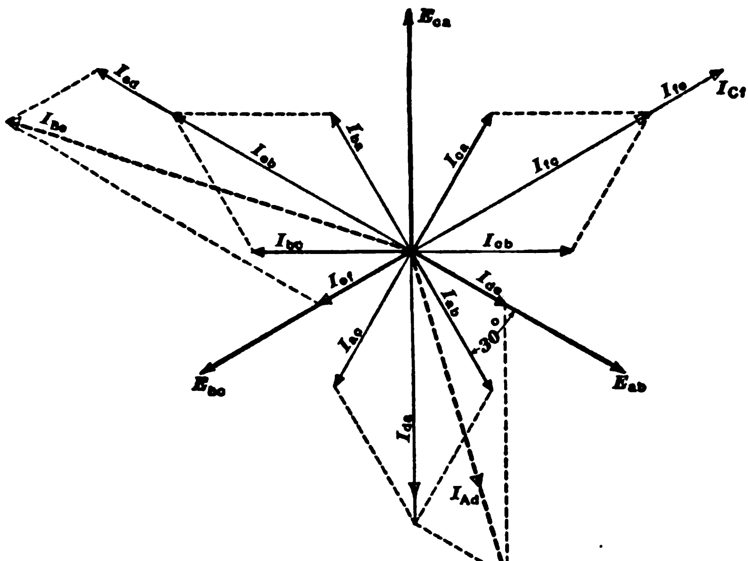


FIG. 47

differing in phase by 120 time-degrees. The power factor of the inductive load, being .866, corresponds to an angle of lag between the voltage and its corresponding current of 30 time-degrees (see Table I). These currents I_{ab}, I_{bc}, and I_{ca} are therefore represented vectorially, as shown in Fig. 47.

The power factor of the lamp load is unity; therefore, I_{de}, Fig. 46, is in phase with E_{ab} and I_{ef} is in phase with E_{bc}. The vectors representing these currents therefore coincide with the voltage vectors, as indicated in Fig. 47.

To find the currents in the three line conductors $d\,a$, $e\,b$, and $f\,c$, Fig. 46, which are the currents caused by the inductive load, equations are written for the points a, b, and c according to Kirchhoff's first law, as follows:

Point a,

$$I_{da}+I_{ba}+I_{ca}=0;\ \text{or,}\ I_{da}=I_{ab}+I_{ac} \qquad (1)$$

Point b,

$$I_{eb}+I_{ab}+I_{cb}=0;\ \text{or,}\ I_{eb}=I_{ba}+I_{bc} \qquad (2)$$

Point c,

$$I_{fc}+I_{ac}+I_{bc}=0;\ \text{or,}\ I_{fc}=I_{ca}+I_{cb} \qquad (3)$$

By means of these three equations, vectors I_{da}, I_{eb}, and I_{fc}, Fig. 47, are drawn, bearing in mind that $I_{ac}=-I_{ca}$, $I_{ba}=-I_{ab}$, and $I_{cb}=-I_{bc}$. With the assumed angle of lag, vector I_{da} is 180° from vector E_{ca}, vector I_{eb} 180° from E_{ab}, and vector I_{fc} 180° from vector E_{bc}.

The total currents in the line conductors A, B, and C are the vectorial sums of those taken by the inductive and non-inductive loads. These sums can be found by writing the equations for points d, e, and f, Fig. 46, according to Kirchhoff's first law; thus,

Point d,

$$I_{Ad}=I_{da}+I_{de} \qquad (4)$$

Point e,

$$I_{Be}=I_{ed}+I_{eb}+I_{ef} \qquad (5)$$

Point f,

$$I_{Cf}=I_{fe}+I_{fc} \qquad (6)$$

By equation 4 the vector of the current I_{Ad} in conductor A is the sum of vector I_{da}, found by equation 1, and I_{de}, which is in phase with E_{ab}, Fig. 47. In equation 5, vector I_{ed} is the reverse of I_{de}, and is in phase with vector I_{eb}; the combined length of vectors I_{eb} and I_{ed} therefore form one component and I_{ef}, in phase with E_{bc}, forms the other, the resultant of these two components being the vector of the current I_{Be} in

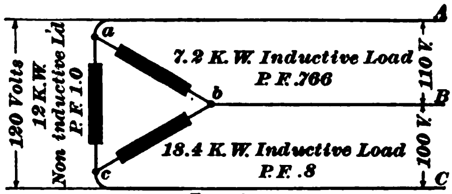


FIG. 48

conductor B. In equation **6**, I_{fe} is the reverse of I_{ef} and is in phase with I_{fc}; the combined length of I_{fc} and I_{fe} therefore gives the vector of the current I_{Cf} in conductor C.

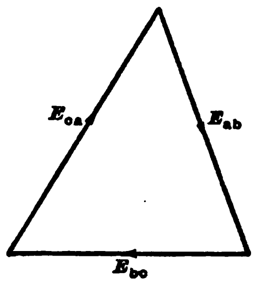


Fig. 49

If the angle of lag were such that I_{ed} and I_{eb} were not in phase, vector I_{ed} would be drawn from the end of vector I_{eb} and vector I_{ef} from the end of I_{ed}, each vector in the direction indicating its phase relation, and a line connecting the free ends of vectors I_{eb} and I_{ef} would then represent vector I_{Be}.

42. Fig. 48 shows conditions found in a certain three-phase circuit by means of measuring instruments. The phases are badly unbalanced, yet the exact phase relations of the currents and voltages can be determined by means of vector diagrams.

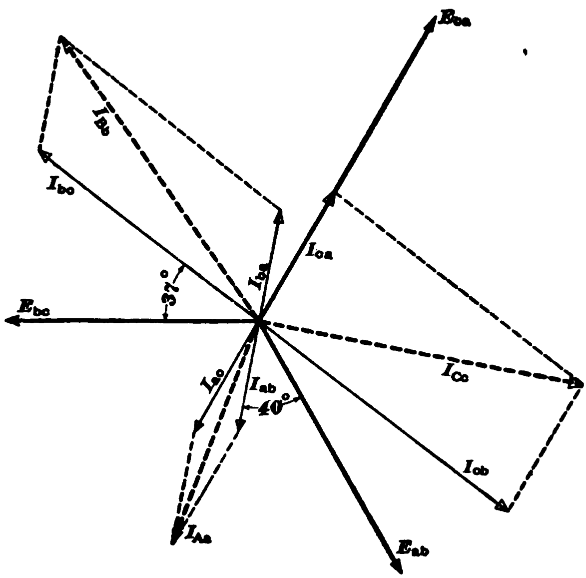


Fig. 50

The phase relations of the voltages can be shown by means of a triangle, Fig. 49, with sides proportional in length to the

three voltages 120, 110, and 100. Radial vectors are then drawn parallel to the sides of the triangle, as in Fig. 50; that is, E_{ab}, E_{bc}, and E_{ca} parallel respectively to the same vectors in Fig. 49.

The current in each phase, Fig. 48, is the quotient of apparent watts divided by voltage, and apparent watts is watts load divided by power factor. The angle of lag of the current behind the voltage corresponding to the power factor in each phase is given in Table I.

$I_{ab}=\frac{7,200}{.766\times 110}=85$ amperes. Angle of lag 40 time-degrees.

$I_{bc}=\frac{18,400}{.8\times 100}=230$ amperes. Angle of lag 37 time-degrees.

$I_{ca}=\frac{12,000}{1\times 120}=100$ amperes. Angle of lag 0 time-degrees.

The vectors of these phase currents are then drawn, as in Fig. 50, I_{ab} 40 time-degrees behind E_{ab}, I_{bc} 37 time-degrees behind E_{bc}, and I_{ca} in phase with E_{ca}. The line currents $A\,a$, $B\,b$, and $C\,c$, Fig. 48, can now be found according to Kirchhoff's first law.

$$I_{Aa}+I_{ba}+I_{ca}=0;\ \text{or, } I_{Aa}=I_{ab}+I_{ac}$$
$$I_{Bb}+I_{ab}+I_{cb}=0;\ \text{or, } I_{Bb}=I_{ba}+I_{bc}$$
$$I_{Cc}+I_{ac}+I_{bc}=0;\ \text{or, } I_{Cc}=I_{ca}+I_{cb}$$

Vector $I_{ac}=-I_{ca}$, $I_{ba}=-I_{ab}$, and $I_{cb}=-I_{bc}$. By adding vectors in Fig. 50 in accordance with these equations, the vectors representing the currents in the line wires are determined.

CALCULATION OF POWER

43. Fundamental Principles.—Whatever may be the number of phases or their interconnection, the power of the balanced polyphase system is always the product of the power in each phase multiplied by the number of phases. The power in each phase is the product of the current, the voltage, and the power factor. When the separate phases have the

same power factor, this power factor applies to the whole system. When the power factors of the separate phases are nearly alike, an average may be considered as the power factor of the system. When the power factors of the separate phases differ greatly, as with unbalanced loads, no power factor applies to the whole system, and the power should be determined for each of the phases separately, as for a single-phase circuit (see Art. 18); the power of the separate phases added together then gives the power of the system.

44. Power in Two-Phase Circuits.—In a balanced two-phase system, either four wire or three wire,

Let P = total power, in watts;
E = phase voltage;
I = phase current, in amperes;
$\cos\phi$ = power factor.

Then, $$P = 2E\,I\cos\phi$$

EXAMPLE.—The voltage across each phase of a two-phase, three-wire circuit is 220, the phase current is 100 amperes, and the power factor is .86. What is the power in kilowatts?

SOLUTION.—According to the formula,
$P = 2\times220\times100\times.86 = 37{,}840$ watts, or 37.84 K.-W. Ans.

45. Power in Three-Phase Circuits.—In a balanced three-phase star-connected circuit, the line current I equals the phase current i, and the line voltage E equals 1.732 times the phase voltage e (see Arts. 35 and 36). The power in each phase is

$$p = e\,i\cos\phi \qquad (1)$$

Substituting for e its equivalent $E\div1.732$ and for i its equivalent I, the power per phase is $\frac{E\,I\cos\phi}{1.732}$. Similarly, in a balanced three-phase delta-connected circuit, the line voltage E equals the phase voltage e, and the line current I is 1.732 times the phase current i (see Arts. 38 and 39). The power in each phase is $e\,i\cos\phi = \frac{E\,I\cos\phi}{1.732}$, as before. In

either case, the total power P is the product of the power in each phase by the number of phases, or

$$P=\frac{3\,E\,I\cos\phi}{1.732}=1.732\,E\,I\cos\phi \qquad (2)$$

EXAMPLE 1.—What power, in kilowatts, is represented by a line current of 150 amperes at unity power factor in a balanced three-phase 6,600-volt circuit?

SOLUTION.—According to formula 2,

$$P=\frac{1.732\times 6{,}600\times 150\times 1}{1{,}000}=1{,}714.7 \text{ K.-W. Ans.}$$

EXAMPLE 2.—Find the total power in an unbalanced three-phase circuit loaded as follows: Phase 1, 120 volts, 100 amperes, non-inductive; phase 2, 100 volts, 230 amperes, 80 per cent. power factor; phase 3, 110 volts, 85 amperes, 77 per cent. power factor.

SOLUTION.—Applying formula 1, $p_1=120\times 100\times 1\div 1{,}000=12$ K.-W.; $p_2=100\times 230\times .8\div 1{,}000=18.4$ K.-W.; and $p_3=110\times 85\times .77\div 1{,}000=7.2$ K.-W. Therefore,

$$P=p_1+p_2+p_3=12+18.4+7.2=37.6 \text{ K.-W. Ans.}$$

ALTERNATORS

TYPES AND CLASSES

1. Generation of Alternating Current.—When a conductor is moved across a succession of magnetic fluxes that have alternately opposite directions, or when the fluxes are made to cross the conductor, alternating electromotive force is induced in the conductor, and alternating current is established in the circuit of which the conductor forms a part. Alternating electromotive force is thus induced in the armature conductors of practically every electric generator. In a direct-current generator, the commutator converts, or rectifies, the alternating current so that the current in the external circuit is direct. An alternating-current generator, commonly called an **alternator,** delivers alternating current to the external circuit.

2. Essential Parts of Alternators.—The two main essential parts of every electric generator are, therefore, the **armature,** or the part that carries the conductors in which electromotive force is induced, and the **field,** or *field magnets,* in which the fluxes are established.

The field magnets of alternators are excited by direct current, which is usually generated by smaller direct-current generators called *exciters*. In large stations, several exciters may feed into one set of bus-bars from which a number of alternators receive exciting current. In rare cases, the alternator is provided with a commutator from which exciting current is taken, and the alternator is then said to be *self-exciting*.

3. Phase.—According to phase, alternators are classed as *single-phase*, *two-phase*, *three-phase*, and *six-phase*. A single-

phase alternator generates one alternating electromotive force; a two-phase, sometimes called *quarter-phase*, alternator, two alternating electromotive forces differing in phase by 90 time-degrees; a three-phase alternator, three alternating electromotive forces 120 time-degrees apart; and a six-phase alternator, six electromotive forces 60 time-degrees apart. The term *polyphase* is a general designation applied to alternators and circuits of more than one phase.

Some two-phase machines are in use, but by far the greater

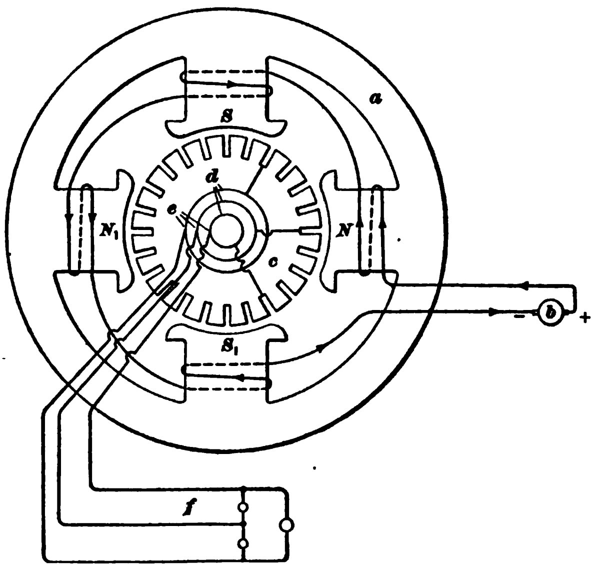


FIG. 1

number of alternators are three-phase machines. Single-phase current is much used, but it is generally taken from individual phases of polyphase machines.

4. Revolving-Armature Alternators.—According to the arrangement of essential parts, alternators are classed as *revolving-armature machines* and *revolving-field machines*. Fig. 1 shows diagrammatically a three-phase revolving-armature alternator. The stationary member consists of a frame *a* supporting magnet poles N, S, N_1, and S_1. These poles are

excited by current from a small direct-current generator *b*. The current produced in the winding of the armature *c* is carried through collector rings *d* and brushes *e* to the external circuit *f*.

Revolving-armature alternators are now so little used that only a general reference to them will be made. Fig. 2 shows a small self-excited machine of this class for use in small, isolated

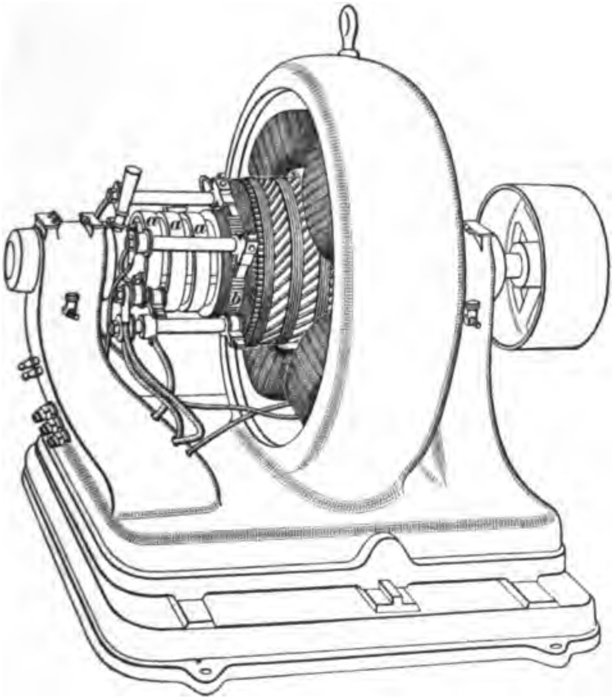


FIG. 2

plants. The three collector rings for the three phases are shown at *a*, and between them and the end of the armature winding is the commutator *b* for rectifying the exciting current, all of which is supplied by a separate winding on the armature. The brushes are mounted on a rocker-arm so that they can be rotated to a position of sparkless commutation of the exciting current. Such generators are not built in large sizes nor for high voltages, because of the difficulties encountered in

insulating the windings and collectors, as well as the danger resulting from exposed collectors.

5. Revolving-Field Alternators.—The demand for greater capacities and voltages is met by the revolving-field alternator, in which only the exciting current is transmitted to the rotating element, or rotor, at relatively low voltage. The revolving-field alternator has almost entirely superseded the earlier type of revolving-armature machines.

Fig. 3 shows a diagram of a three-phase revolving field alternator. The field *a* has four poles N, S, N_1, and S_1. The

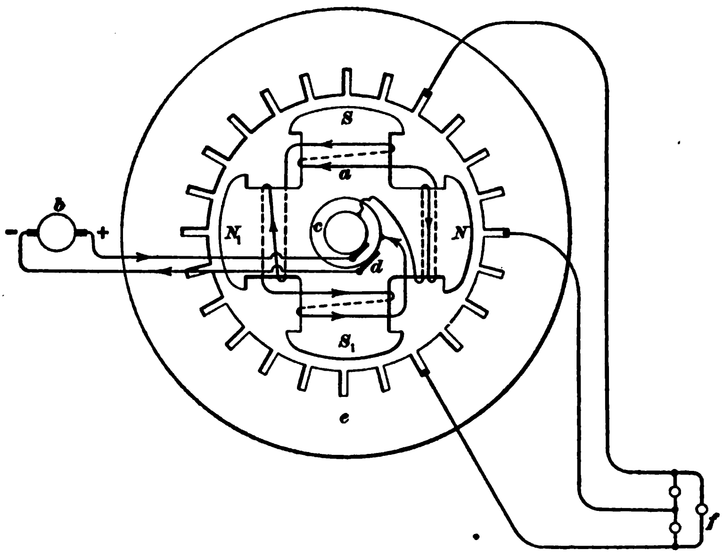


FIG. 3

windings on these poles are connected to the exciter *b*, through collector rings *c* and brushes *d*. The stationary armature *e* is provided with slots on the inner periphery to receive the winding in which the electromotive force is generated. The terminals of the winding are connected to the external circuit *f*.

6. Method of Rating Alternators.—The most common method of rating alternators in the United States is in *kilovolt-amperes*, which is abbreviated k. v. a., read by pronouncing the

letters *k v a* separately. One kilovolt is 1,000 volts. If I is the current per terminal and E the volts between terminals, the kilovolt-amperes for a single-phase circuit is $\frac{I\,E}{1{,}000}$; for a two-phase circuit, $\frac{2\,I\,E}{1{,}000}$; and for a three-phase circuit, $\frac{\sqrt{3}\,I\,E}{1{,}000}$. The rating in kilovolt-amperes means the same as the rating in kilowatts at unity power factor. If an alternator is rated in kilovolt-amperes, its output in kilowatts is equal to the product of the kilovolt-ampere rating and the power factor at which it is operated; thus, a 10,000 kilovolt-ampere alternator will deliver 9,000 kilowatts at a power factor of 90 per cent.; 8,000 kilowatts at a power factor of 80 per cent.; and so on. The rating in kilowatts is sometimes specified, but it is indefinite unless accompanied by the statement of the power factor.

7. Methods of Driving Alternators.—Alternators may also be classed as *belt* or *rope driven*, *steam-engine driven*, *gas- and oil-engine driven*, *water-wheel driven*, and *steam-turbine driven*. Each of these classes has some special features of construetion, on account of the speed and characteristics of its driver, but the essential features are the same for all.

A belt-driven alternator is usually purchased complete with bearings, shaft, and pulley ready to receive the driving belt. There is also generally provided a sliding base and a screw device for adjusting the belt tension. The rotating element of an engine-driven alternator is generally pressed on an extension of the engine shaft, and the engine and alternator form a compact unit. Alternators driven by waterwheels and steam turbines are usually coupled to the driving shaft. The name *turbo-alternators* is sometimes applied to turbine-driven alternators, and the prefix *steam* or *water* indicates the kind of turbine.

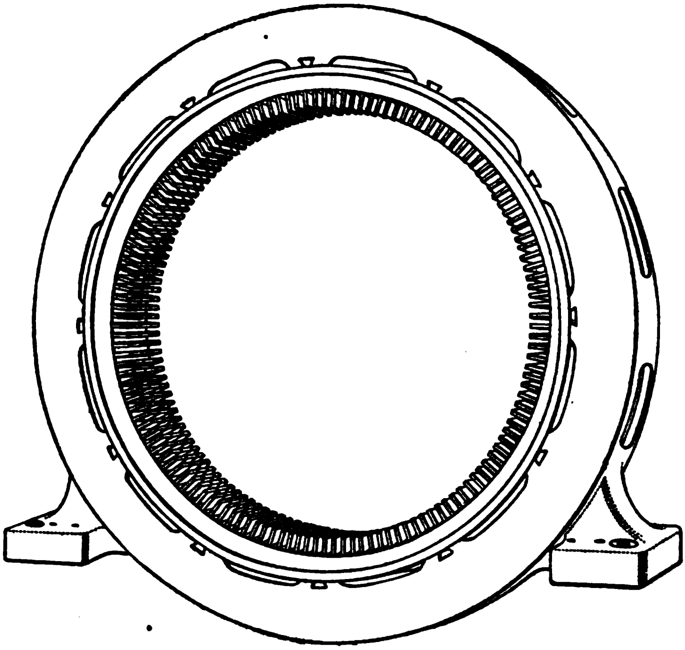


FIG. 4

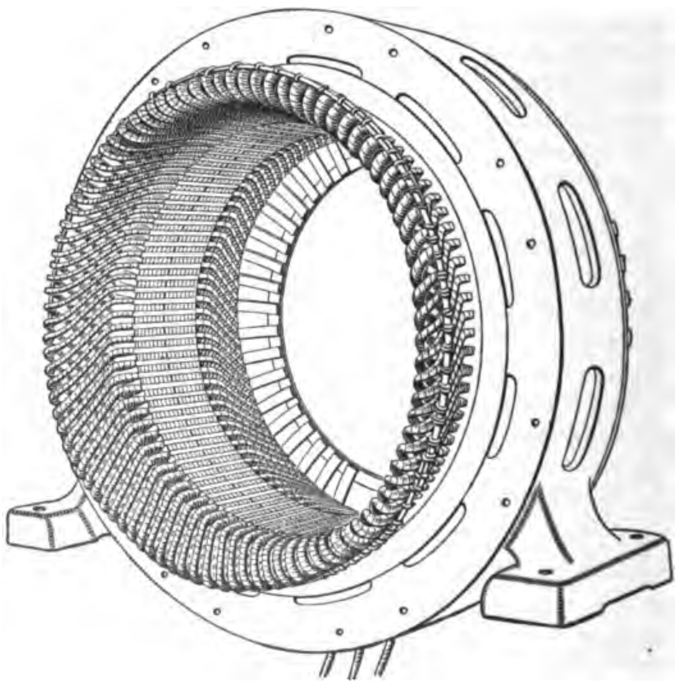


FIG. 5

STRUCTURAL FEATURES

STATOR CORES

GENERAL APPEARANCE

8. The **stator,** or *stationary part,* constituting the armature of a revolving field alternator consists essentially of a laminated iron core and its supporting structure; the core is located inside the structure and carries the stator windings in slots in its inner cylindrical surface. Fig. 4 shows the assembly of a core in a supporting frame, and Fig. 5, a complete stator with the windings in place. When the rotor is in place and the machine complete, guard rings, or brackets, one of which can be seen on the rear of the stator, extend over the projecting windings and protect them. Alternator stators differ in details of design, according to size and to differing judgments and tastes of designers, but the general appearance is as shown.

LAMINATIONS

9. Material.—The stator laminations are punched from large sheets of soft iron selected for low hysteresis loss. Stator cores are laminated for the same reason as those in the armatures of direct-current machines, namely, to reduce eddy currents. The sheets are thin in order to keep the eddy-current loss as low as possible, because these currents vary as the square of the thickness of the laminations; .014-inch laminations are in general use.

10. Methods of Punching.—Laminations with outer diameters not exceeding 12 inches are generally punched in one piece; those of larger outer diameter are punched in segments, as will be shown later. The number of segments to form a circle is chosen with reference to the number of slots, preferably

so that dividing lines between segments come at slot centers; if the teeth are very wide, the divisions can well be made at tooth centers.

11. Stator Slots.—Open stator slots, such as those shown in Fig. 6 (*a*), (*b*), (*e*), (*f*), and (*i*), are generally used in American made alternators. The forms shown in (*a*), (*b*), and (*e*) are most commonly used. The coils are held in place in open slots by wooden or fiber wedges *a* in dovetails near the top of the teeth.

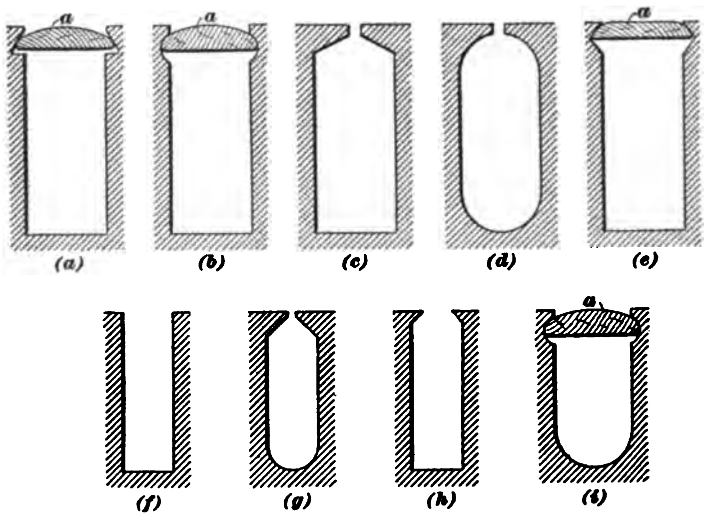


Fig. 6

With open slots, the coils can be completely formed and insulated before being placed in the slots, thus generally permitting better workmanship and lower cost than is feasible with the semiclosed slots shown in (*c*), (*d*), (*g*), and (*h*). In the latter, the windings must be fed through the narrow openings between tooth tips. This advantage of open slots may become especially important to the operator in case repairs are essential. Semiclosed slots have some advantages from a design standpoint and they can be used with little difficulty when the slot conductors consist of single bars that can be thrust endwise through them.

12. Annealing and Insulating.—The action of the die in punching the laminations hardens them. Therefore, to remove this hardness so as to minimize hysteresis loss, the sheets are annealed before assembling the cores. Insulation is essential between laminations to prevent eddy currents. This insulation may be very thin; a layer of enamel or japan baked on is sufficient.

ASSEMBLY

13. One-piece stator-core punchings are usually assembled inside supporting ribs in the frame, being keyed or dove-

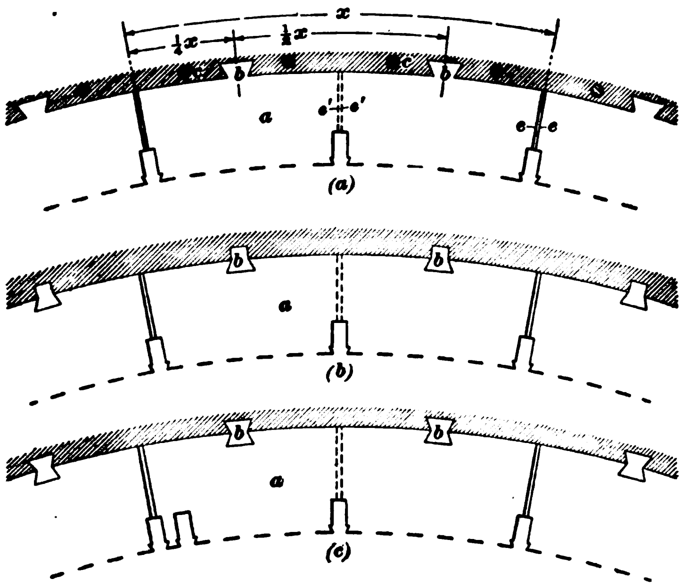


FIG. 7

tailed to them to prevent turning. Clamping rings that are pressed against the ends of the core and then keyed prevent axial movement.

14. Segmental punchings are assembled in several ways. Some of the most common methods are shown in the sectional views, Fig. 7, in which only enough slots are indicated on each segment to show the dividing lines between segments.

In the method shown in view (*a*), each segment *a* is held in place by two dovetail projections *b* that fit into corresponding slots milled in the cast-iron supporting frame. The laminations are clamped between end plates secured by bolts *c*. The ends of the punchings are cut a little less than the full arc *x*, giving a small clearance *e e* between abutting ends and thus making the laminations go into place more easily. The next layer of laminations is put on so that the joints come midway between the joints of the first layer, as shown at *e′ e′*; thus, the joints of no two adjacent layers are in line with each other. Other kinds of dovetail supports are shown in views (*b*) and (*c*). The dovetail pieces *b* are fastened to the frame, and notches are punched in the laminations, thereby requiring less iron than if the sheet were large enough to make the dovetail a part of the lamination.

Since the core slots must be smooth and perfectly alined, the ends of long steel keys the exact size of the slots are usually driven into a few slots after several laminations are in place, and the remaining laminations are assembled on these keys.

15. Air Ducts.—At intervals in the core are ducts for the passage of air that cools the armature. These ducts are formed by means of suitable spacers, or spacing strips. Enough spacing strips must be used to support each tooth securely—two per tooth for wide teeth.

16. Clamping.—In order to prevent vibration of the teeth under the rapidly changing magnetism, they are well braced not only in the air ducts, but also at the ends. Spacing strips, or end fingers, are used between the core and the end flange, a finger bracing each tooth. Sometimes the fingers are cast integral with the end flange, especially when the flange is cast in segments. The core is firmly pressed together, and the flanges are keyed or otherwise fastened. Cores more than 16 inches long are usually pressed every 10 or 12 inches during assembly; this practice is very common with vertical cores. The final pressure is very heavy, sometimes several hundred tons for long cores. The flanges are secured between a shoulder on one end of the stator spider and keys on the other end.

17. Preparation of Slots.—The slots should be smooth so as to prevent the insulation on the conductors from being cut. The method of assembling described insures fairly smooth slots, but each slot is finished either by slightly filing it or by driving through it a *broach*, that is, a piece of steel having the sides fluted to form cutting edges. At the ends, the slot corners are filed smooth and round to avoid cutting the insulation where the coils are bent around the corners. No more filing or broaching should be done than is absolutely necessary, since it burrs the metal so as to form paths for eddy currents close to the insulation on the conductors, where the heating caused by these currents will be most detrimental.

STATOR WINDINGS

BAR WINDINGS

18. Stator windings are of two general types, based on the form of conductor used, namely, *bar windings* and *coil windings*. If the capacity of the machine is such as to permit the

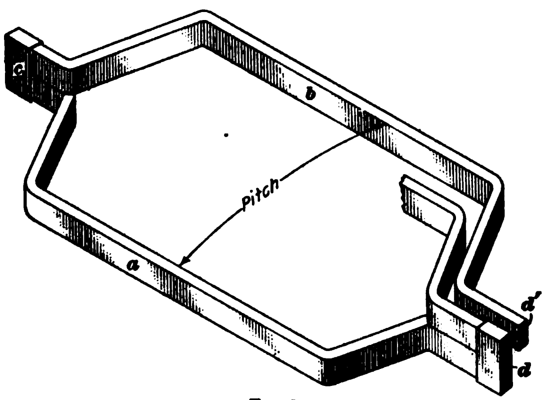


FIG. 8

use of very few conductors per slot, they are usually in the form of insulated bars. All bar windings are in two layers; that is, two insulated bars are laid, one over the other, in each slot or

four bars are laid in two pair, one pair over the other. Bar windings may be considered in two classes, according to the form of the end connections of the bars, as *lap* and *wave windings*.

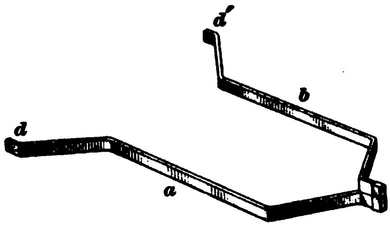


FIG. 9

19. The **lap winding** is the most common form of bar winding. The bars, as shown in Fig. 8, are so shaped that they can be connected in pairs forming loops, of which one side *a* fits in the bottom of a slot and the other side *b* fits the top of another slot at the proper distance, or pitch, from the first. The ends of bars forming a loop are joined, one over the other, by a clip *c* securely soldered in place; the other ends *d* and *d'* are joined with corresponding ends of other coils. The fact that

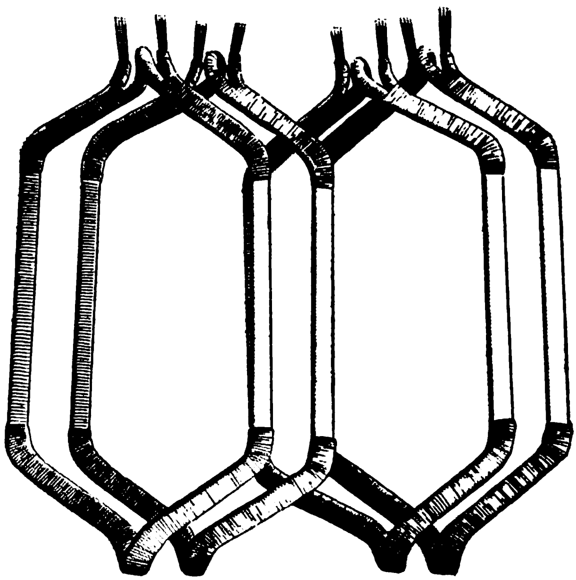


FIG. 10

these front-end connections *d* or *d'* approach each other so that the circuit of which the coil forms a part overlaps itself,

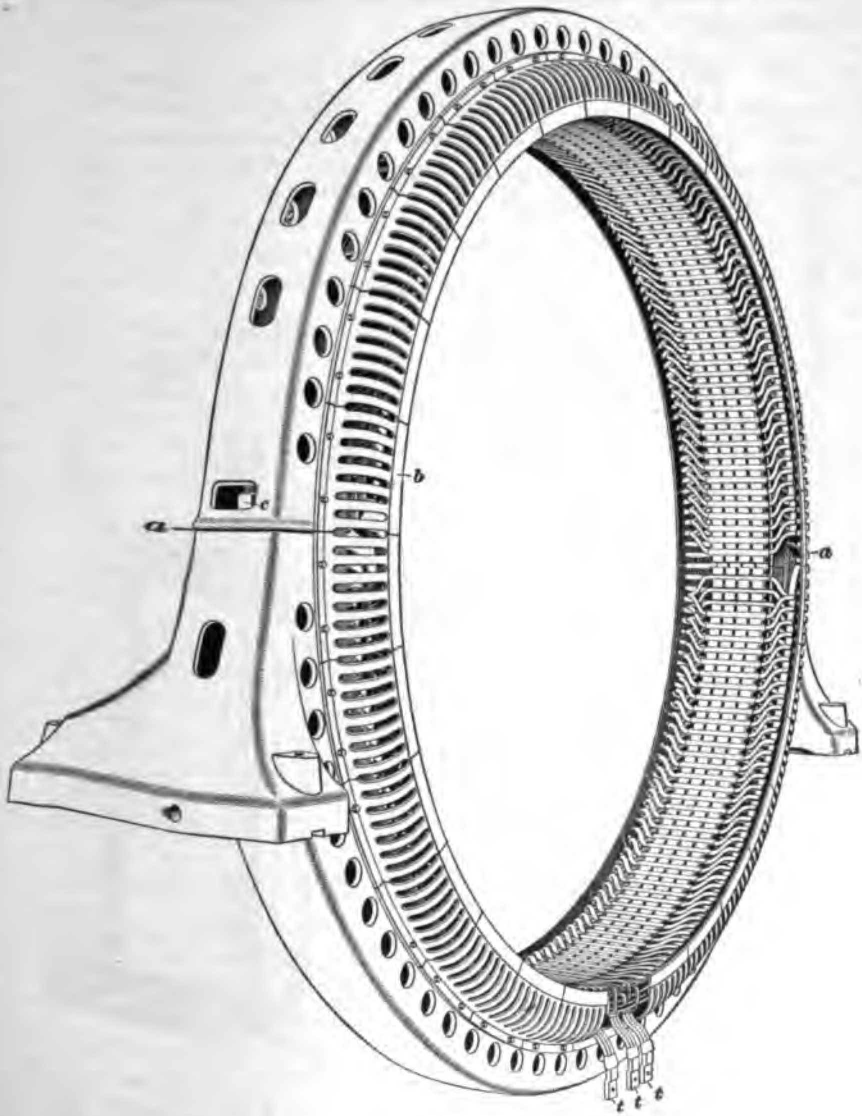


Fig. 11

as on a parallel wound direct-current armature, gives this winding its name.

20. Bars forming a loop, or turn, for a **bar wave winding** are shown in Fig. 9. They differ from those of the lap-wound coil in that the ends *d* and *d'* are separated, as on a series-wound direct-current armature. The letters *a b c* have the same signification here as in Fig. 8.

COIL WINDINGS

21. Two-Layer Winding.—If many conductors are used per slot, they are arranged in coils, which may be of either the two-layer or the one-layer type. Four coils of the two-layer type are shown in Fig. 10. The only essential difference between these coils and the loop shown in Fig. 8 lies in the number of turns per coil. Fig. 11 shows a stator wound with two-layer coils. This stator is in two parts, divisible at planes *a*, where the omission of a few coils is indicated; these coils are installed in the completed stator. The ventilated end shields are shown at *b*, and the head of a bolt for holding the two parts of the frame together is shown at *c*. The terminals of the stator winding are shown at *t*.

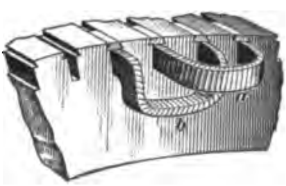


FIG. 12

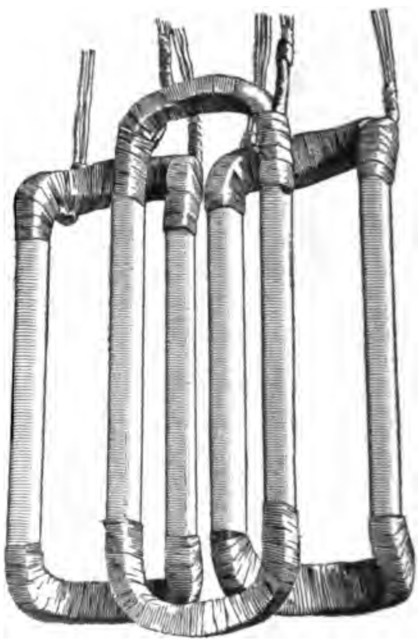


FIG. 13

22. One-Layer Chain Winding.—One-layer coil windings are of the *chain type* and the *basket type*. Fig. 12 shows two coils of the chain type; each side of a coil fills a slot, and the ends of the coils interlink, as shown at *a* and *b*. Fig. 13 shows a set of three coils for a three-phase chain winding with three slots per pole, one slot per phase per pole, and Fig. 14 shows the appearance of such coils assembled on the stator core, the coil interconnections showing at *a*. Fig. 15 illustrates coils for a three-phase chain winding with two slots per pole per phase. The part of the insulated coil that is to lie in the slots is usually molded under pressure and is encased in leatheroid, which serves as mechanical protection against injury when placing the coils in the slots.

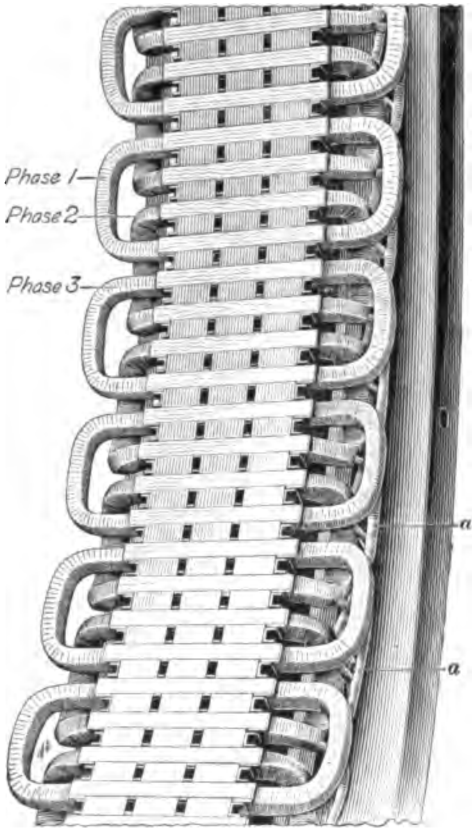


FIG. 14

23. Fig. 16 illustrates different kinds of single-layer chain windings used on alternator stators with three, four, and six slots per pole. The coils of each phase are shown in distinctive color, and the method of drawing them indicates how they are interlinked at the ends. The spacing is indicated in electrical degrees, the space between centers of two successive north poles being 360 electrical degrees. Empty

slots may occur when punchings for polyphase machines are used for the cores of single-phase machines, as shown in (*a*) and (*f*); omitting either phase in (*c*) would give a single-phase winding with two empty slots per pole.

24. **One-Layer Basket Winding.**—The basket winding shown in Fig. 17 consists of coils of uniform shape that cross one another at the ends. This winding is little used on alternators, its use being confined mostly to small alternating-current motors.

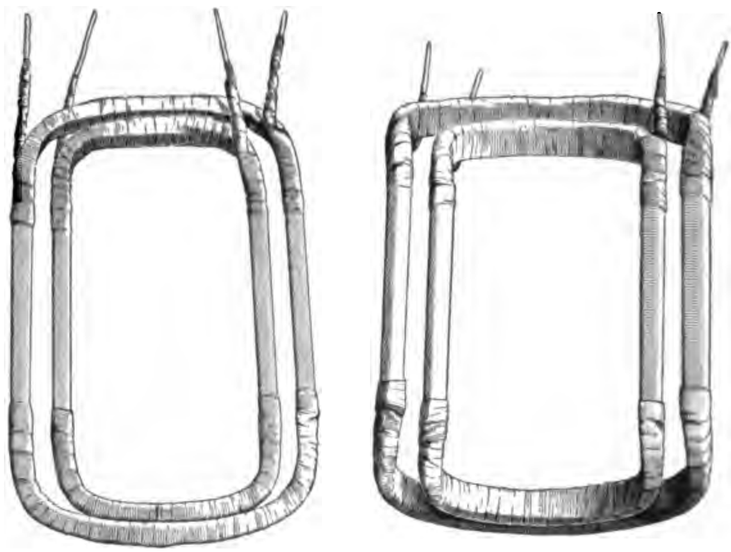


FIG. 15

25. One-layer windings have the advantage of more economical use of slot space than two-layer windings. One-layer chain windings also have the advantage of greater separations of coil ends outside the slots, but they have the disadvantage of requiring several different forms of coils for a machine. The basket winding obviates this disadvantage, but, in turn, it has the disadvantage of massing, or crossing, at the ends, thus making good insulation and ventilation more difficult.

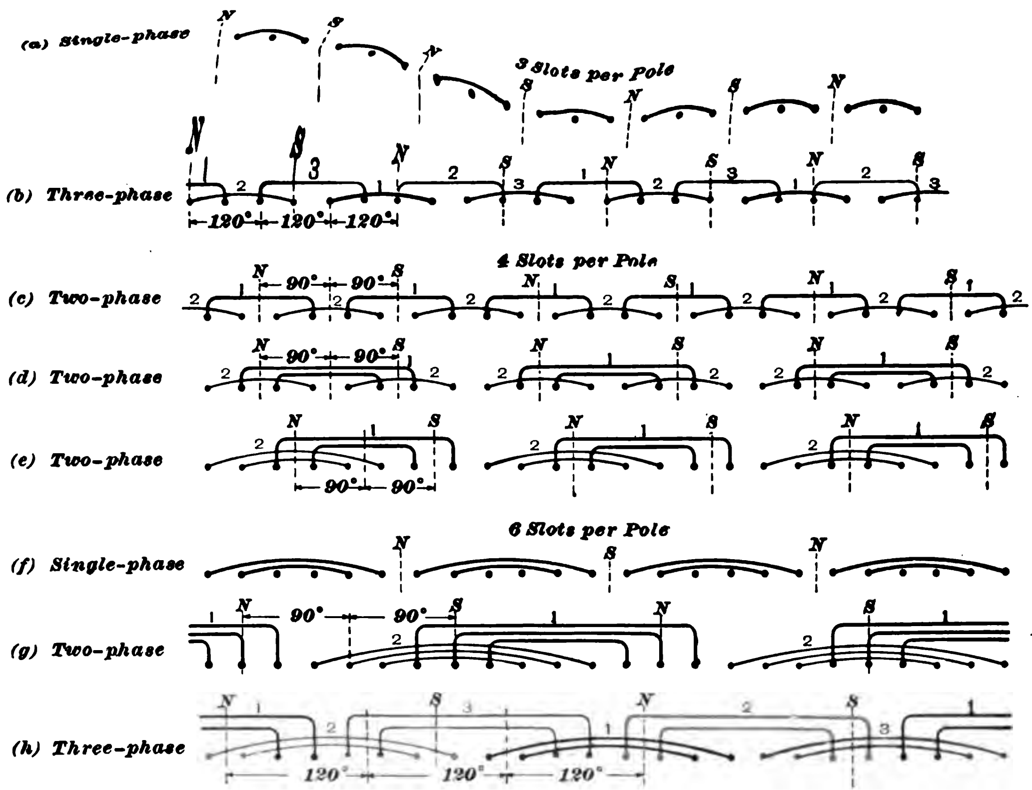

3 Slots per Pole
(a) Single-phase
(b) Three-phase
4 Slots per Pole
(c) Two-phase
(d) Two-phase
(e) Two-phase
6 Slots per Pole
(f) Single-phase
(g) Two-phase
(h) Three-phase

FIG. 16

26. One-Layer Slot, Two-Layer End Winding.—A type of winding unit having one layer in the slot and two layers at the ends is shown in Fig. 18. One side of the coils projects a short distance straight from the slots, as at *a*; then it turns and continues to a point *b*, where a compound turn

Fig. 17

or twist, is made to pass under the ends of neighboring coils, as at *c*; and, finally, it turns upwards and into the plane of the slots at *d*. The other ends of the coils are duplicates of the ends shown, except that conductor ends are brought out for connections. This winding utilizes slot space economically

and requires but one form of coils. The complicated bends, however, are hard to make, especially with heavy copper, and

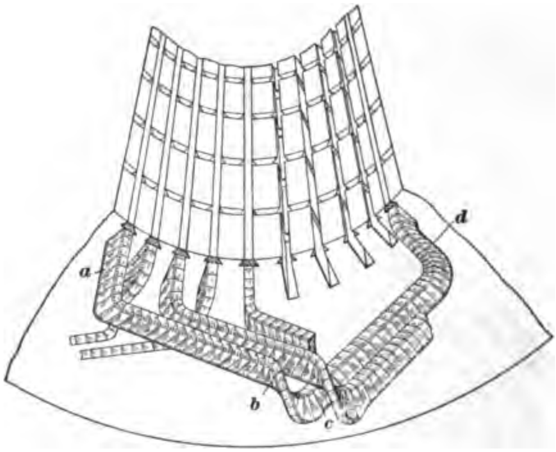


FIG. 18

the insulation and ventilation of the coil ends are not so easy as with chain windings.

STATOR CONDUCTORS AND COILS

27. Conductors.—Fig. 19 shows cross-sections of alternator slots with different forms of conductors. Round wire, as in (*a*), is used for small coils of many turns, although it does not fill the slot space so economically as square wire. However, square wire gives so much trouble by twisting at the bends in the coils that it is seldom used.

Flux crossing the slots between teeth is most dense near the air gap, thus causing slightly higher voltage in the part of a solid conductor near the top of a slot than in the part near the bottom. To prevent useless eddy currents from this cause, sectional, or stranded, conductors are generally used when large current capacity is needed. In some cases, such conductors are employed only in the tops of the slot, where eddy currents would be strongest, as in (*c*), (*d*), and (*e*); in other cases both the top and the bottom conductor are composed of strands, as in (*f*) and (*g*).

Fig. 19 (*b*), (*c*), (*d*), and (*e*) show sections of bar windings in which the coils are formed in halves and connected after placing them in the slots. This method permits the use of different conductor sections in the top and the bottom of the slot. In (*c*), the upper conductor is a cable pressed into a rectangular

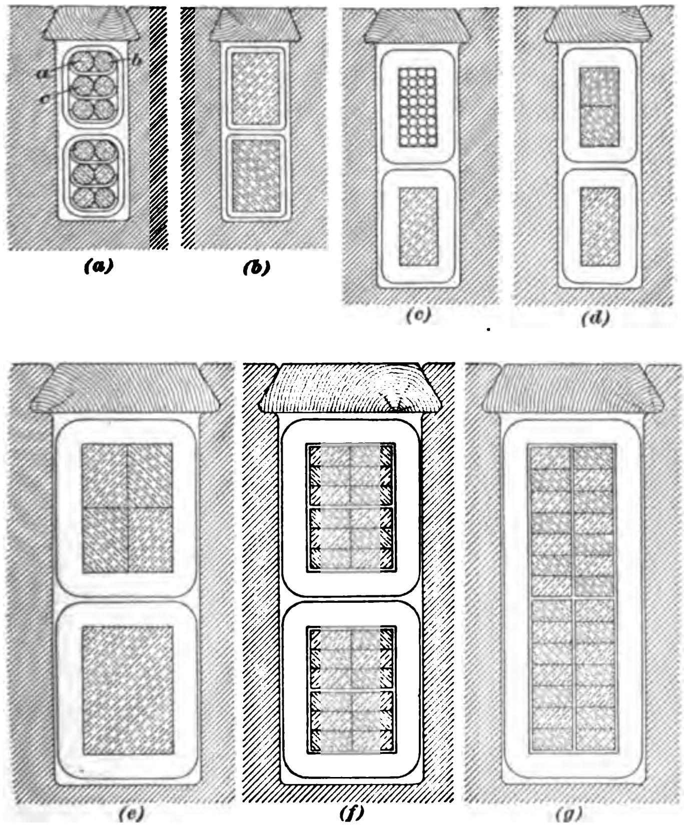


Fig. 19

cross-section; in (*d*) it is divided crosswise with a thin layer of insulation in the division; and in (*e*) it consists of four strands of rectangular copper. Views (*a*) and (*f*) show two-layer coil windings, the former with round wire and the latter with rectangular wire, and (*g*) shows a single-layer coil winding with

rectangular wire. In both (*f*) and (*g*), the coils are sectionalized by cross-divisions of insulation that is thick enough to prevent eddy currents.

28. Coil Formation.—Accurately made forms are required to shape the coils. Some of these coil forms are comparatively simple wooden structures; others are of metal and sometimes very complicated and expensive. The construction of coil forms to shape coils only for repairing machines is seldom good economy, provided complete coils can be purchased of the alternator manufacturer.

29. Insulation of Conductors.—Sectionalizing conductors to prevent eddy currents can usually be done with very thin insulation. For example, oxidation on the copper wire is enough in the pressed cable shown in Fig. 19 (*c*); .005-inch paper serves in conductors shown in (*d*) and (*e*), and single cotton for the rectangular wire shown in (*f*) and (*g*).

The insulation between turns of a coil must be proportional to the voltage between adjacent conductors in the coil. For example, if each turn of the coil shown in Fig. 19 (*a*) generates 10 volts, this voltage exists between successive turns *a* and *b*; but between turn *a* and the third turn *c* in the series, that is, between layers, the voltage is 20. Each turn is therefore wrapped with some insulating material, such as cotton cloth impregnated with varnish, and **U**-shaped pieces of paper or fiber are placed between layers. In coils with higher voltages per turn, the conductors may be insulated with varnished cambric or mica tape, the latter consisting of thin layers of mica cemented to thin paper, the whole being about .005 inch thick. Mica tape is protected from mechanical injury by an outer wrapping of cloth tape.

30. Insulation of Coils.—The manner in which coils are insulated depends on their formation and on the voltage of the machine. The *impregnation process* is much used for coils of several turns. The formed coils are wound with a temporary covering of tape and then placed in a tank in which the temperature is raised to a high degree and from which the air is

exhausted. The heat and the vacuum combined remove every trace of moisture and practically all the air from the insulation. After this, hot insulation compound is forced in under pressure. The compound thus enters all the crevices between conductors, as well as the pores in the insulation. When the coils are removed the compound solidifies, and the coil remains a solid mass at all operating temperatures. The compound not only helps to insulate, but also readily conducts heat from the interior of the coil to the exterior. The temporary taping is removed from impregnated coils after they have cooled, and permanent wrappings are substituted, covering all except the ends for connections.

Bar windings are insulated similarly to coils, but they are not impregnated. The materials used in insulating bars, and the number of wrappings, depend on the voltage. For low voltage, varnished or oiled cloth tape is sufficient; for high voltage, mica tape covered with cloth tape may be employed. The parts of the coils or bars in the slots are usually covered with an armor of tough material to prevent mechanical injury.

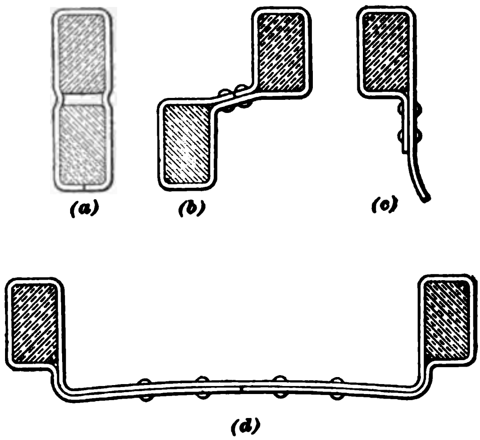


FIG. 20

31. Assembly.—Properly formed coils fit very closely in the slots; in fact, some force must be used to press them into place. The ends of bars are then joined by clips as shown in Fig. 20. The clip shown in (*a*) is for bars that are in the same axial plane as at *c*, Fig. 8; that in (*b*), for ends in slightly different planes; and that in (*c*), for leads to the connection board. The clip shown in (*d*) is called a *pole connector*, as is explained later. All clips are well insulated with tape, shellac, etc.

32. Since the stator core slots are radial, coils must be somewhat distorted in placing them in the slots, especially when the slots are deep, as on large machines. Small low-voltage coils are flexible enough to be easily pulled out so that they will slip into the slots; large coils are heated to make the insulation more flexible. After the coils are in place, their ends are connected by means of suitable clips and solder; then they are insulated and the whole winding is coated with moisture-proof varnish.

ROTOR CONSTRUCTION

GOVERNING FEATURES

33. A **rotor** for a revolving-field alternator consists of direct-current electromagnets arranged to rotate inside the stator core. The magnetic circuits of these electromagnets are thus completed through the stator core. The rotor construction depends on the peripheral speed, that is, on the diameter and the number of revolutions per minute. For slow-running, engine-type alternators, a series of poles is bolted or dovetailed to a cast-iron spider, as in Fig. 21. For peripheral speeds of 6,000 to 8,000 feet per minute, as in waterwheel alternators, cast-steel spiders are used; for higher speeds, up to 10,000 feet per minute, the poles are secured to a laminated steel rim carried on arms and a hub of cast iron or steel; and

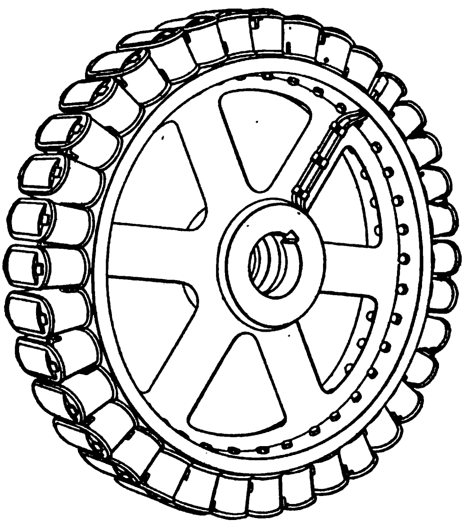


FIG. 21

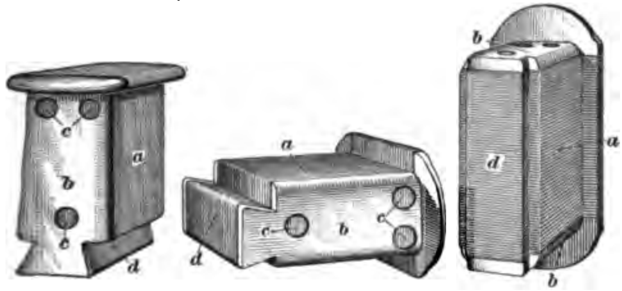


FIG. 22

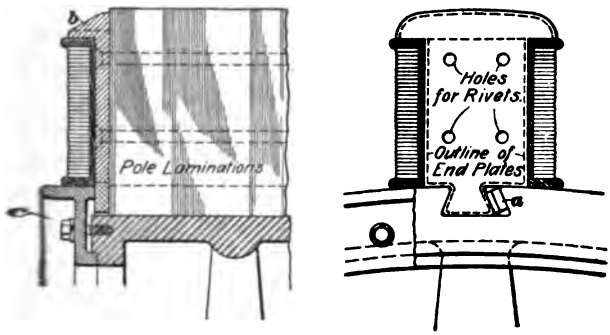


FIG. 23

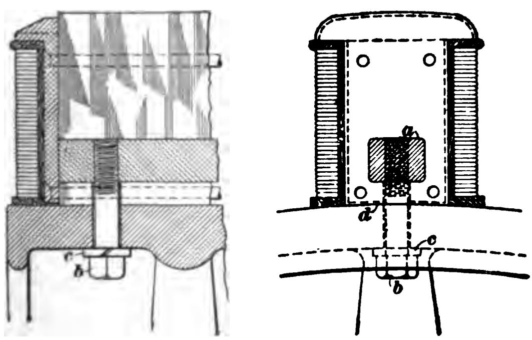


FIG. 24

for still higher speeds, as in steam-turbine alternators, very special rotor construction is essential. Such construction is described in connection with steam-turbine alternators.

SALIENT-POLE ROTORS

34. Dovetail Construction.—Rotors such as those shown in Fig. 21, in which the poles are separated from each other by intervening air spaces or by some non-magnetic material, are called *salient-pole rotors*. The poles are made of laminations assembled and riveted between end plates, as shown in Figs. 22 and 23. At *a*, Fig. 22, are shown the laminations; at *b*, the end plates; at *c*, the rivets; and at *d*, the dovetail that fits into a groove in the spider rim and is held by steel wedges *a*, Fig. 23. The field coil fills the space formed by the overhanging pole and the flanged end plate *b* above and the clamping ring *c* below; this ring is bolted to the spider. The laminated structure is to prevent in the structure itself eddy currents due to changes of magnetic density as the poles pass the stator teeth.

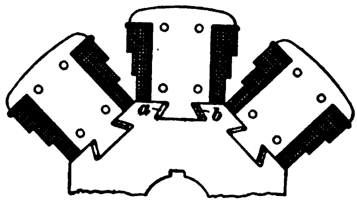


Fig. 25

35. Bolted Construction.—Fig. 24 shows the method of bolting poles to the spider rim. An opening is punched in each lamination, and these openings form in the pole a space into which a bar *a* is inserted. Stud bolts *b* through the spider rim

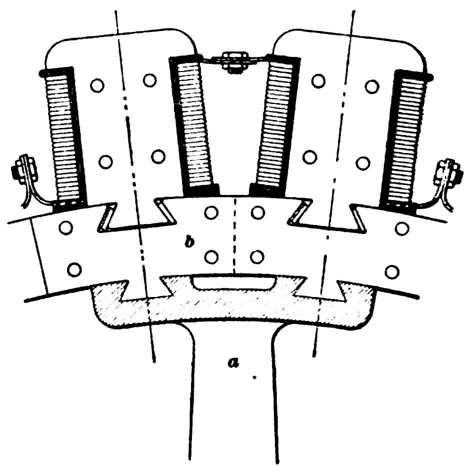


Fig. 26

are screwed into tapped holes in this bar, and they are held secure by lock washers *c*. The contact surface *d* between the pole and the rim is not so large as with dovetail construction, but the difference in the reluctances of the magnetic circuits is not appreciable if the machine work is well done. Bolted construction is not generally good magnetically with cast-iron rims, nor is it considered so strong mechanically as dovetail construction.

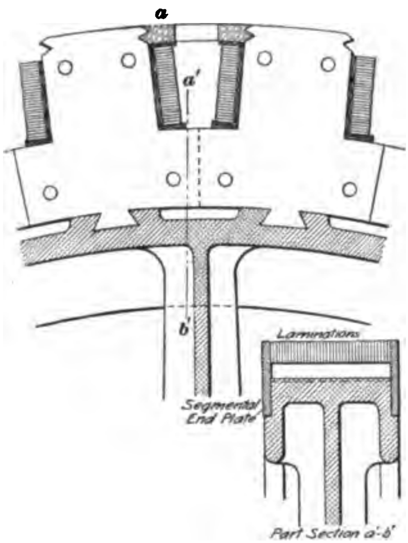


FIG. 27

36. Laminated Spiders and Rims.—Fig. 25 shows the construction of a small rotor in which laminated poles are dovetailed into a laminated spider assembled on the shaft. Shims *a* form a surface against which to wedge the dovetail when the keys *b* are driven home. The coils are tapered because of the narrow space available near the spider. Fig. 26 shows the construction employed for high-speed rotors, in which the spider arms *a* carry a laminated rim *b* riveted between end plates. Fig. 27 shows a section of a rim and the poles of continuous laminations. The coils are held in place by pieces *a* of cast copper or brass; these pieces act also as dampers to prevent sudden variations of speed when the alternator runs in parallel with others. A laminated rim with staggered joints is much stronger than one of cast iron or cast steel.

ROTOR WINDINGS

37. Coil Construction.—Rotor fields are usually excited by direct current from a 125- or a 250-volt circuit. Round wire is employed for the coils when the exciting current is small, and flat copper strip wound on edge, as in Fig. 28, for larger current. The latter construction is better mechanically, and, besides, it dissipates heat from the interior more readily; hence, it is employed wherever the current is large enough to justify its use. Fig. 28 (*a*) shows a pole piece, a short-circuiting collar, and an insulating collar, and (*b*), a strip-wound coil pulled apart to show the construction. The short-circuiting collar is placed on the pole next to the flange, in which position

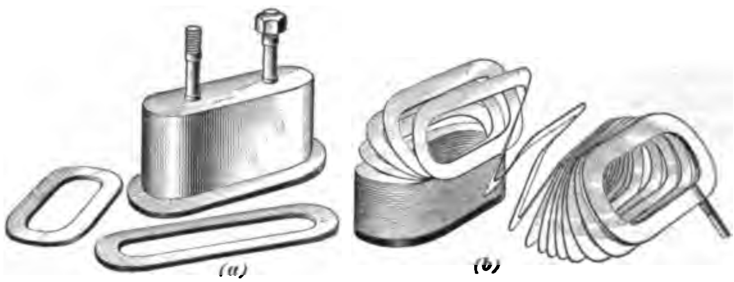


Fig. 28

it serves to steady the flux in the pole. Next to this collar comes the insulating collar, then the coil, which is insulated and cemented together, and lastly another insulating collar next to the rim of the spider.

38. Assembly.—The field voltage is so low that a high degree of insulation is not needed, but the heavy mechanical stresses require very secure assembly to prevent any movement of the coil. Figs. 23 to 27, inclusive, show coils in place, and Fig. 26 shows connections between coils. All the coils are wound alike, and the correct polarity is obtained by making the interconnections alternately at the top and the bottom. On high-speed rotors, these connections must be supported by insulated clamps.

MISCELLANEOUS PARTS

COLLECTORS

39. The **collector** on a revolving-field alternator carries the exciting current from the stationary to the rotating part of

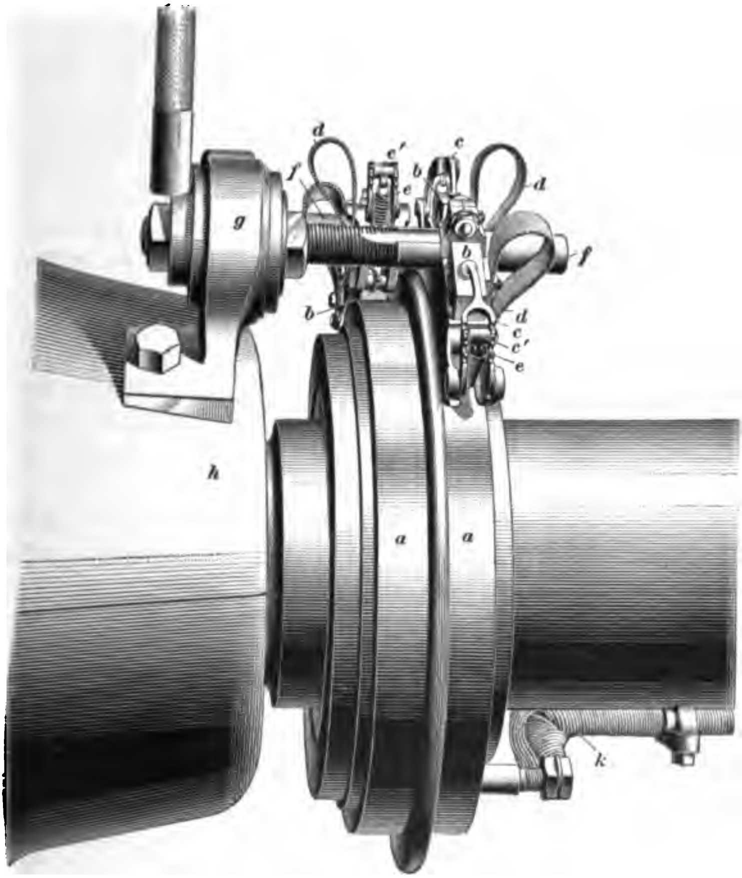


FIG. 29

the circuit. It consists essentially of two collector rings sliding under stationary brushes. The complete collector includes

all the means for supporting and holding the rings, brushes, and connections. It may take any one of several forms.

Fig. 30

One form of collector is illustrated in Fig. 29. The rings are shown at *a*, and at *b* are shown the brushes, which are held on the rings by fingers *c* and springs *e*. The pull of the springs can be adjusted by placing their supporting casting *c'* in different notches in the forks of the fingers. Woven-wire cables, or *pigtails*, *d* furnish low-resistance current paths between the holders and brushes. The brush holders are carried on studs *f* supported by castings *g* mounted on the bearing housing *h*. The connections leading from the collector rings to the field coils are well insulated, wrapped with cord, as at *k*, and securely fastened to the shaft.

Large alternators, especially those for direct connection to engines, usually have brush holders supported on pedestals or on brackets attached to the stator frame. Fig. 30 shows one form of pedestal for this purpose; the connections to the brush-holder studs are carried up through the interior of the pedestal.

40. **Rings.**—The collector rings are usually made of cast iron; they are mounted on a shell, or spider, one form of which is shown in Fig. 31. In this case, both the rings and the spider

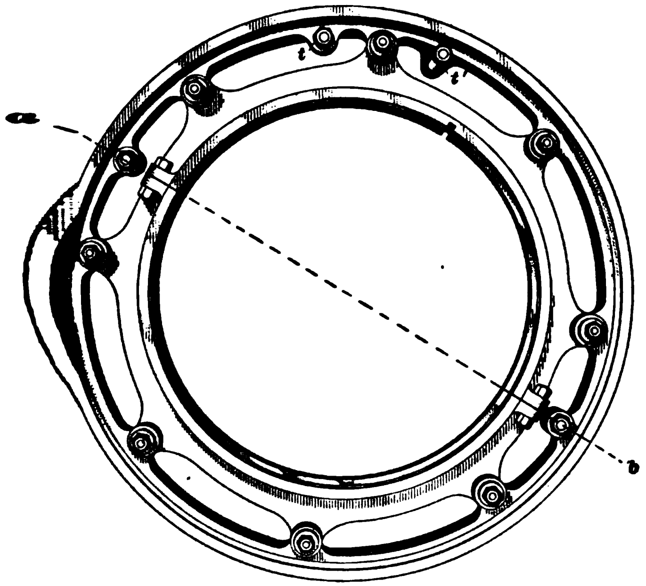


Fig. 31

are split on the line *a b* to facilitate ready removal without dismantling the machine. Split rings are unnecessary on small machines that may be easily dismantled. Fig. 32 shows a method of supporting the rings on pins *a* encased in molded

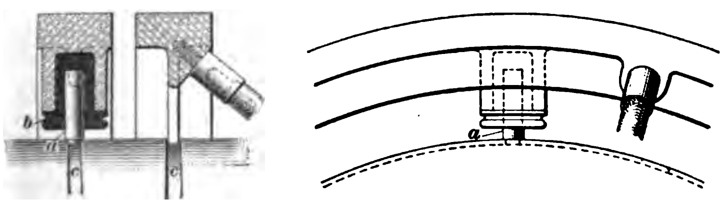


Fig. 32

insulation *b* and fitted into holes in the bottom of grooves *c* in the shaft. These holes prevent the ring from turning on the shaft.

Fig. 33 shows two methods of clamping split rings. In view (*a*), a conical washer *b* is clamped against a conical seat, half

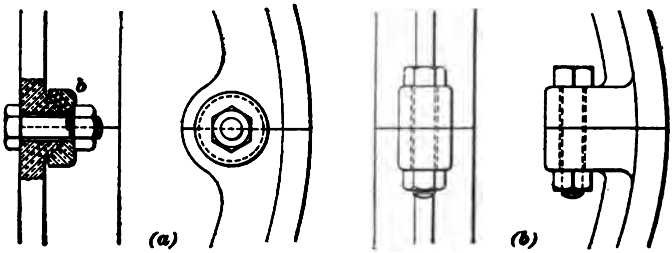


FIG. 33

of which is part of each half of the ring; in (*b*), use is made of bolts that pass through lugs on the ring segments.

41. Brush Holders and Brushes.—Brush holders are made in endless variety. In most cases, each brush holder consists essentially of a stationary box in which a brush slides freely and a spring-actuated device for holding the brush against the ring.

Brushes made of carbon or of graphite, or of a mixture of the two materials, are most frequently used. They work well on rings of any material, especially on cast-iron rings, which take a high polish. Brushes made of other materials, such as mixtures of carbon or graphite with copper dust, are sometimes used, especially if high conductivity is desirable.

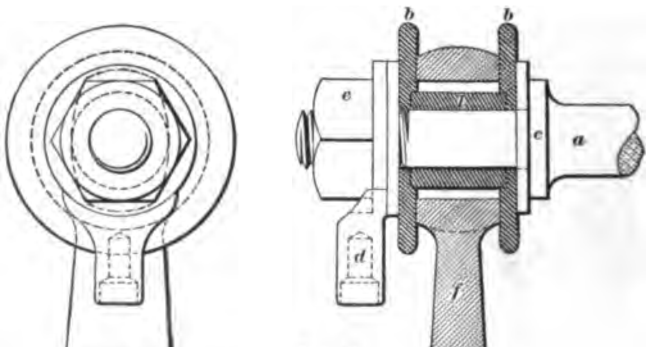


FIG. 34

42. Brush-Holder Support.—Fig. 34 shows a method of supporting the stud *a* on which the brush holders are clamped.

The arm *f* has a slotted opening in which the stud is clamped and in which its position can be adjusted to bring the brushes nearer to the rings or farther from them. The stud is insulated from the arm by a sleeve *l* and washers *b* placed between metal washers. One of these metal washers rests against a shoulder *c* on the stud, and the other serves as a base for the washer part of terminal *d*, outside of which is a clamping nut *e*. The arm *f* corresponds to the arm *g*, Fig. 29.

BEARINGS

43. Alternator bearings are practically always self-alining and self-oiling, the usual construction being as shown in Fig. 35. The bearing rests on a spherical surface *a*, permitting it to aline itself perfectly with the direction of the

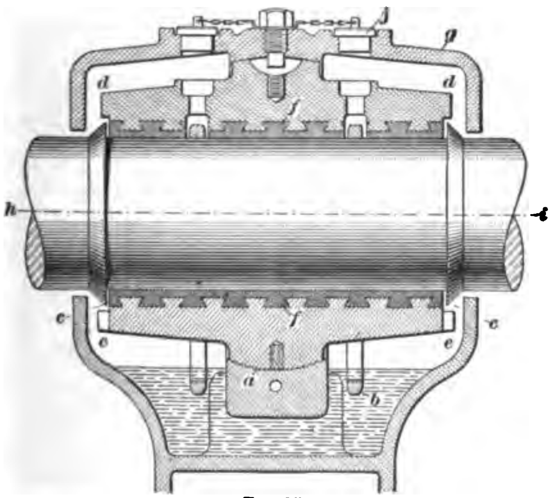


Fig. 35

shaft. Oil rings *b* hang in slots in the upper half of the bearing and dip into oil in the reservoir below; these rings, resting on the shaft, turn with it and carry oil to the top of the shaft, whence it is distributed through grooves in the bearing surface.

The collars *c* on the shaft limit the end movement and prevent oil from escaping along the shaft. The lips *d* on the bearing catch the oil thrown from the collar and deliver it to

the oil chamber below, a section of each lip being cut away at *e* for this purpose. The Babbitt lining *f* is held in the shell by dovetails. The top part of the bearing housing *g* can be removed, the joint of the two parts being along the horizontal plane *h i*. The oil rings can be inspected through the sight holes *j*.

VENTILATION

44. Air circulation for ventilating the cores and windings, where heat is occasioned when the machine is operating, is provided by the fanning action of the rotor and its ventilating vanes, which action causes air to pass through the various openings and air ducts. Fig. 36 shows a cross-sectional view made in a plane that includes the center of an alternator shaft. This alternator has a laminated field rim, such as is shown in Fig. 27, permitting air ducts through the field rim and poles to match those in the stator core. When the field rim is solid, holes are made in it for the passage of air.

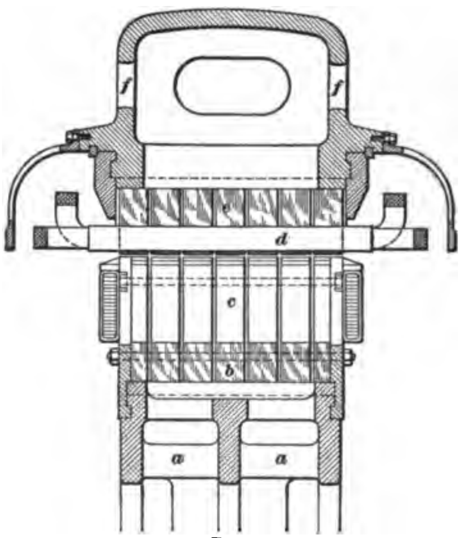


FIG. 36

When the alternator, Fig. 36, is operating, air passes from the center out through openings in the spider rim and between the arms at *a*, through ducts in the laminated rim *b* and the pole piece *c*, past the stator windings *d*, through the ducts in the stator core *e* into the frame, and out through the numerous openings *f*.

Short machines do not require holes or ducts in the field rim, because they receive enough air through the spaces between the poles, as at *a'*, Fig. 27.

SPECIAL STRUCTURAL FEATURES

ENGINE-DRIVEN ALTERNATORS

45. By *special structural features* is here meant those necessary to fit an alternator for a particular service or a particular method of drive. The general construction already described

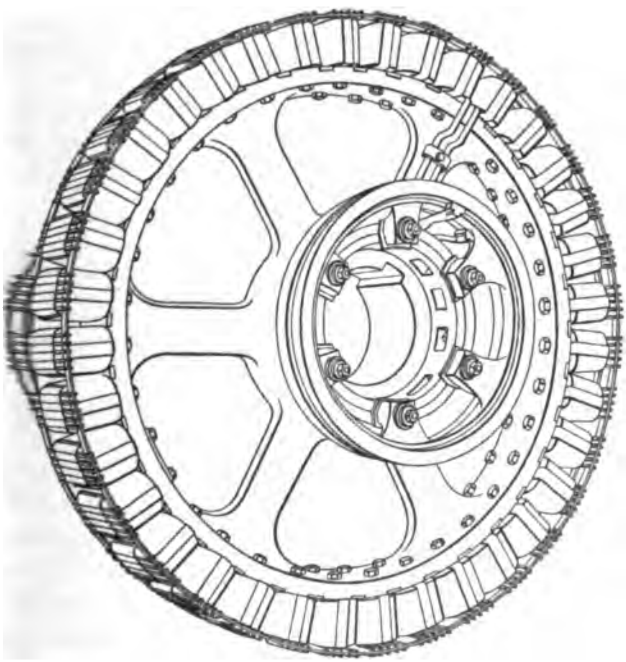


FIG. 37

applies to some features of the following machines, and only those features differing from preceding descriptions will be considered.

46. Alternators direct-driven by reciprocating steam engines and gas or oil engines are usually of large diameter and short length. When operated in parallel with other alternators, measures must be taken to eliminate slight inequalities of peripheral speed that otherwise occur with reciprocating-engine drive. Such measures usually consist of heavy flywheels, either separate from the rotor, but on the same shaft, or as a part of the rotor construction, in what are known as *flywheel alternators*.

For gas- or oil-engine drive, where the peripheral speed is less uniform than with steam engines, the flywheel is made heavier, and in some cases a special *squirrel-cage winding* is placed over

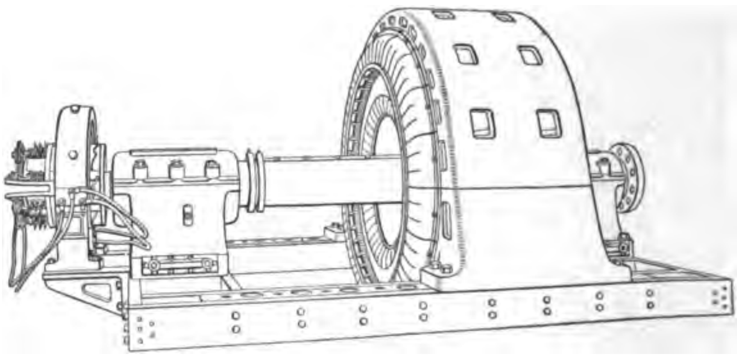


FIG. 38

the pole faces, as in Fig. 37. This winding serves to hold the speed constant; it is fully explained in connection with alternating-current induction motors.

47. Flywheel Alternators.—The distinguishing feature of flywheel alternators is the heavy construction of the spider rim, which construction gives the rotor the necessary inertia, or flywheel effect. The large diameter and the resulting high stresses necessitate secure attachment of poles, as in Figs. 26 and 27, and also heavy frame construction to obtain rigidity. The stator frames of large engine-type alternators are usually shipped in sections, and provisions are made for securing the joints, as in Fig. 11.

48. Ventilation.—Engine-type alternators are usually cool in operation because of the large surface per unit loss and because of ample air movement. The only difficulties met with are the discharge of heated air into the pit in which the lower part of the frame hangs and the reentrance of this air to the machine. These difficulties, when serious, are overcome by omitting the openings in the part of the stator frame below the floor level so that heated air is discharged only above the floor.

49. Facilities for Repairs.—The engine and the alternator are assembled as a unit, the bedplate, the bearings, and the shaft being supplied by the engine builder; also, the alternator is usually arranged so that the windings can be made accessible for repair without taking the engine to pieces. A very good method is to provide for sliding the complete stator axially until it is clear of the rotor, as is explained later in connection with Fig. 38; another method is to provide for raising the upper half of the stator, but this necessitates the removal of a few stator coils at each joint, as in Fig. 11.

WATERWHEEL-DRIVEN ALTERNATORS

50. The speed of waterwheels depends on the pressure of the water. Alternators for waterwheel drive are therefore designed for speeds ranging from that of reciprocating engines to that of slow-speed steam turbines. The construction for all speeds must be very substantial to resist the heavy mechanical stresses that accompany a sudden removal of the load; the driving power is not susceptible of quick control and the speed may increase from 50 to 100 per cent. before the water can be shut off. Two types of waterwheel-driven alternators are in use, *horizontal-shaft machines* and *vertical-shaft machines*.

51. Horizontal-shaft alternators for waterwheel drive resemble very closely the engine-driven machine, but they are supplied complete with bedplate and pillow-block bearings, as shown in Fig. 38. This illustration shows a direct-connected exciter at one end and space for sliding the stator toward the exciter to gain access to the windings.

52. Vertical-shaft waterwheel alternators are distinguished chiefly by the bearing construction. Guide bearings maintain the rotor in a vertical position, and a thrust bearing in connection with the alternator or the waterwheel supports the weight of the revolving parts of both. The guide bearings, which take only the side pressure, are less substantial in construction than the bearings of a horizontal machine of the same weight; besides, they require a different method of lubrication. Provision is made by pumping, by elevated oil reservoirs, or otherwise to force the oil into the vertical bearings.

53. Thrust Bearings.—Thrust bearings are of two types, namely, *disk bearings* and *roller bearings*.

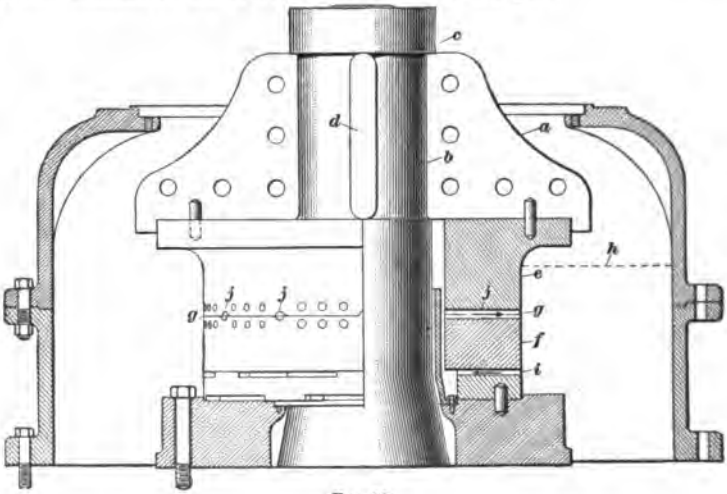


FIG. 39

54. In the **disk bearing,** shown in Fig. 39, a collar *a*, in halves, is bolted around the shaft *b* immediately under the shaft collar *c* and is driven by a key *d*. Below this rotating collar is the rotating part *e* of the bearing, it being separated from the stationary part *f* by the bearing surface *g*. Oil stands in the chamber at the level *h* and enters openings *i* in the stationary part; when the shaft is rotating, centrifugal force causes circulation of the oil out through radial openings *j* between the bearing surfaces, as indicated by the arrows.

The **roller bearing** is practically the same in construction as the disk bearing, with the addition of rollers between the moving and stationary parts.

55. Ventilation.—Large horizontal-shaft alternators of the waterwheel type are often supplied with fans to insure uniform temperatures throughout the machines. This is especially true when the speed is so high that braces are necessary between the rotating poles. Such braces interfere with air circulation, sometimes necessitating fans at the ends of the rotor.

Vertical-shaft alternators may be ventilated from either end or from both ends. The openings in the top are relatively small and must be covered with gratings to prevent the entrance of coarse articles, such as tools. The more desirable method is to introduce air from below, preferably taking it from outside the building when weather conditions permit. The use of fans and guide vanes is generally necessary to direct the air in the proper paths.

STEAM TURBO-ALTERNATORS

STRUCTURAL FEATURES

56. The chief distinguishing structural features of steam-turbine-driven alternators are their small dimensions, as com-

TABLE I

COMPARATIVE FEATURES OF ALTERNATORS

Feature	Engine-Driven	Water-wheel Driven	Steam-Turbine Driven
Capacity, kilovolt-amperes	1,500	1,500	1,500
Revolutions per minute	100	360	1,800
Diameter at armature face, inches	180	72	28
Length of armature core, inches	12	20	26
Peripheral speed, feet per minute	4,700	6,700	12,700
Ratio of diameter to length of core	15	3.6	1.08

pared with other alternators of equivalent capacity, and the rotor construction. In order to avoid excessive peripheral speed with the high rotative speeds of steam turbines, these alternator rotors are comparatively long and of small diameter. Even with these dimensions, the peripheral speeds are much higher than in other alternators, necessitating very special rotor construction.

The comparative features of engine-, waterwheel-, and steam-turbine-driven alternators are indicated in Table I.

STATOR CONSTRUCTION

57. Cores.—The stator cores of steam-turbine-driven alternators are constructed essentially the same as those of other alternators, except that, on account of the excessive

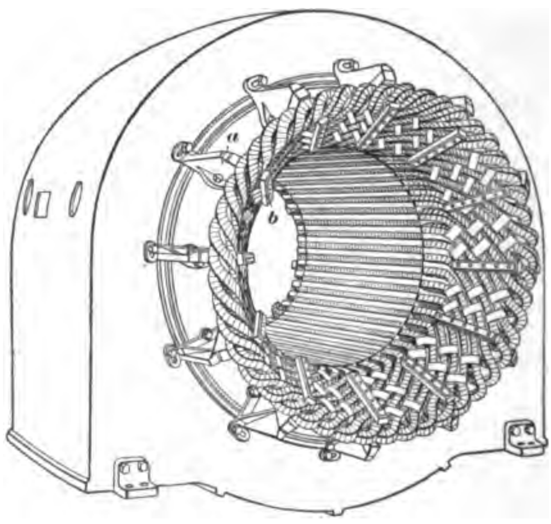


FIG. 40

length, special precautions must be taken to insure a tight core. For this reason, the frame and the flanges are much more massive than those of other types of alternators of similar diameter.

58. Windings.—The conductors for such stators are bars, pressed cables, or groups of rectangular strands, as shown in Fig. 19, slots (*b*) to (*g*), inclusive. Slot (*b*) shows general practice with small turbo-alternators, and the other slots, in order, represent the practice with increasing sizes up to slot (*g*) for the largest. The stator conductors in very large alternators must be of large cross-section, and they usually consist of rectangular strands, from 20 to 40 such strands, as shown in slot (*g*), being sometimes employed.

59. During the first half cycle, accidental short circuits cause transient armature current from 10 to 30 times normal value, decreasing in approximately 2 seconds to the established current of from 1.5 to 3 times normal current. This established current lasts as long as the short circuit and the field excitation are continued. The excessive transient overload causes heavy stresses tending to pull the coils out of shape, and secure bracing is therefore necessary. Fig. 40 shows one method of securing the coils; in addition to wedges in the slot portions, the coil ends are clamped between braces *a*, bolted to the frame and strips *b*, the clamping bolts passing through ventilating spaces in the windings. Another method is to lash the coil ends to a heavy insulated metal ring encircling them, this ring being fastened to the ends of braces like those shown at *a*; in this case, the strips *b* are omitted, and wooden blocks are secured between the coil ends to prevent sidewise movement.

ROTOR CONSTRUCTION

60. The most distinctive feature of steam turbo-alternators is the rotating-field structure. Several methods of construction are in use, all of which may be considered in two general classes, namely, *laminated-body rotors* and *solid-body rotors*. For large capacities at high speeds, the tendency to vibration becomes so great that the rotor shaft and body must be made solid in order to secure the requisite strength.

61. Laminated Rotors.—Fig. 41 shows a laminated field in process of construction. The core *a*, with ventilating

ducts *b* and dovetail grooves *c*, is assembled on a cast-steel spider, and the poles are made of laminated blocks *d*, *e*, and *f* dovetailed and wedged in the grooves *c*. Blocks adjacent to the field coils, such as *d* and *e*, are shaped to form slots; in this field, when completed, other rows of blocks and two additional field coils are placed outside those shown, making four coils per pole. The rivet heads on the blocks meet in the air ducts, thus maintaining the proper spacing. In some cases,

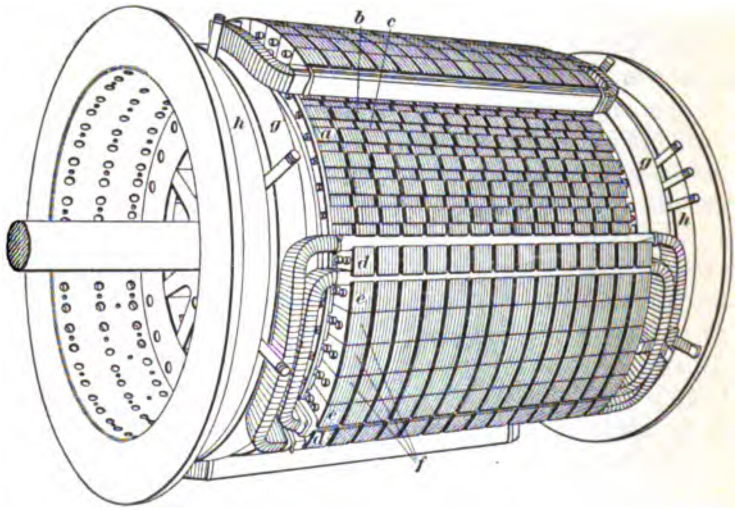


FIG. 41

the core *a* is made of solid steel plates of a thickness to form one of the sections between ventilating ducts.

The ends of the two inner field coils rest on retaining rings *g*, and the ends of the two outer coils (not shown), on rings *h*. The bolts projecting between the retaining rings are some of those serving to clamp plates over the coil ends, giving the finished appearance shown in Fig. 42, in which *a* indicates a clamping plate and *b* holes therein for ventilation.

62. Solid-Body Rotor With Radial Slots.—Fig. 43 shows a partly finished radial-slot rotor body and shaft machined from a solid steel forging. Large axial grooves are

still to be milled in the enlarged parts of the shaft next the rotor body for ventilating the ends of the field coils.

The complete rotor appears as in Fig. 44. The field coils are held in the slots by brass or steel wedges *a* driven into dovetail grooves near the tooth tips. Perforated seamless nickel-steel rings *b* are heated and forced over supports with a close fit; when the rings cool, they shrink against the supports with a stress somewhat greater than the centrifugal force when in operation, thus preventing looseness. These rings cover and protect

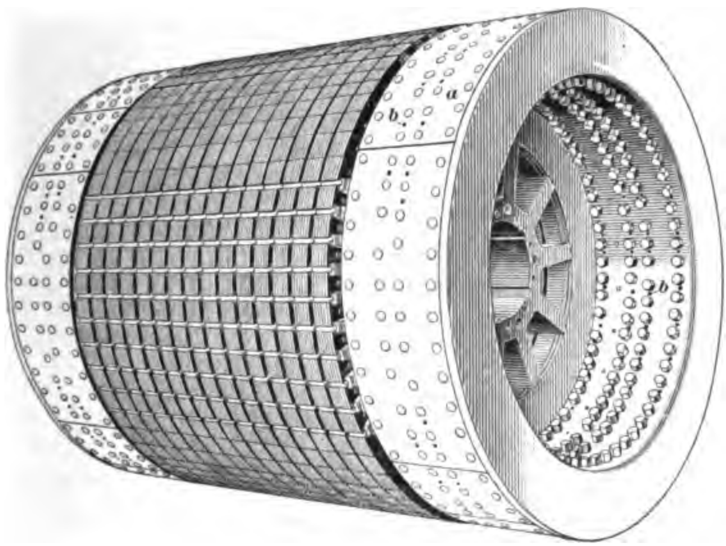


Fig. 42

the coil ends and bind them firmly in place. Ventilation of the coil ends is obtained through the perforations *c* and grooves *d*, the fans assisting in maintaining air circulation. No means are provided for admitting air to the body of the rotor, but the conductors are large enough to make the losses small, and the heat is absorbed and dissipated by the massive rotor body.

63. Solid-Body Rotor With Parallel Slots.—Fig. 45 shows the method of constructing a solid forged-steel, two-pole

FIG. 43

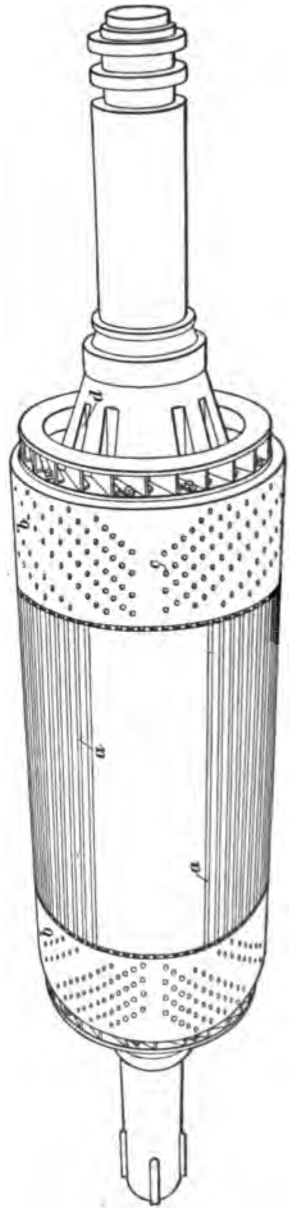


FIG. 44

rotor body with slots milled in parallel planes. These slots extend lengthwise and across the ends of the rotor body, so

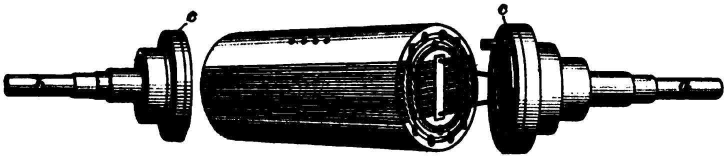


FIG. 45

that the field coils are entirely embedded. Fig. 46 shows a cross-sectional view of this rotor body. The coils *a* are copper strips tightly wound in the slots and held by metal wedges *b*, this construction being used also across the ends. The journals *a* and *b*, Fig. 45, are turned with heavy shoulders that are bolted to the rotor body with intervening bronze disks *c* to prevent magnetic leakage from the rotor body.

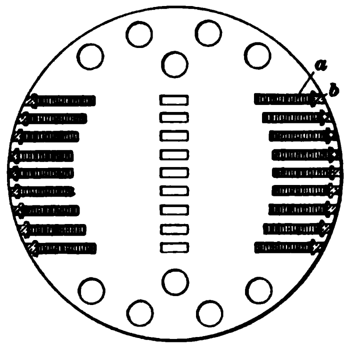


FIG. 46

64. Fig. 47 shows a four-pole rotor body constructed according to the same principle, but with salient, or projecting, poles to permit greater space for copper. In this case,

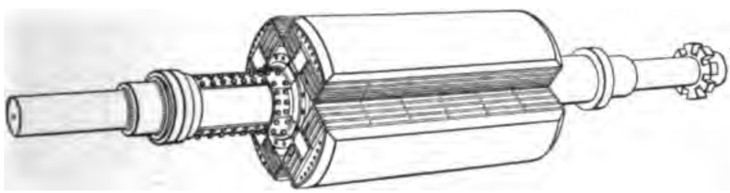


FIG. 47

the body and the shaft are in one piece; however, the journals are sometimes made separate, as in Fig. 45, in order to reduce the size of forging required.

MISCELLANEOUS PARTS OF STEAM TURBO-ALTERNATORS

65. Collector Rings.—In order to resist high centrifugal stresses and to obtain contact surfaces that run absolutely true, the general practice is to shrink forged iron or steel rings over steel shells with intervening mica cylinders about $\frac{1}{16}$ inch thick. The rings are heated and placed over the insulated shell, and, on cooling, they shrink tightly against it, making a very substantial construction. The shell is pressed and keyed on the shaft, and the ring surfaces are then finished true.

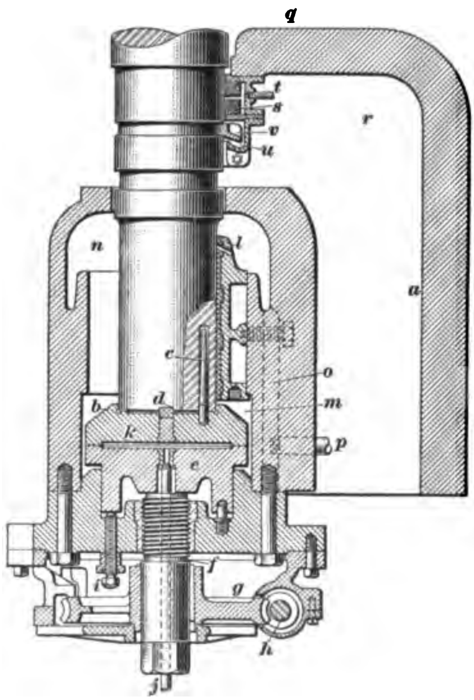


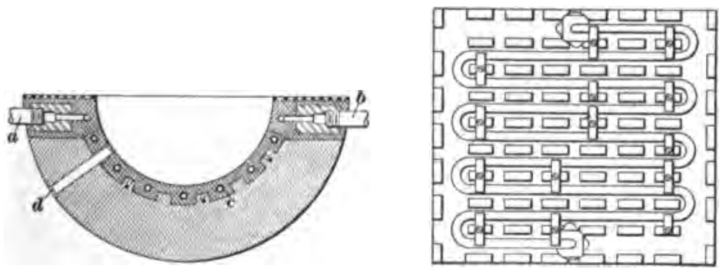
FIG. 48

66. Bearings for Vertical-Shaft Steam Turbo-Alternators.—Fig. 48 shows a combination step and guide bearing, which is placed in the lowest part of the turbine base *a*. A rotating bearing plate *b* is attached to the lower end of the shaft by pins *c* and key *d*. Below the rotating plate *b* is a stationary plate *e* supported on a screw *f*, by means of which the position of the whole rotating member can be adjusted by turning the worm-wheel *g* through the worm-screw and shaft *h*. Screws *i* serve to aline the stationary plate *e* with the rotating plate *b*. A pipe *j* extends through the adjusting screw to the annular space *k* between the rotating and stationary plates. Oil is forced into the space

under a pressure of 500 to 800 pounds per square inch, which pressure is sufficient to lift the whole rotating element a few thousandths of an inch and float it almost frictionless. The mechanism thus far described constitutes the *step bearing*.

The *guide bearing* *l* is lined with bearing metal at the shaft surface. It is oiled by the overflow from the step bearing. Oil from the annular space *k* enters the chamber *m* with sufficient pressure to force it up between the shaft and the guide bearing to chamber *n*, from which it returns to the source of supply through a passage in the structure *o*, not shown, and pipe *p*.

The wall *a* of the base separates the condenser chamber *q* from the bearing chamber *r*. Chamber *r* is at atmospheric pressure, and chamber *q* at a pressure considerably below



(a) FIG. 49 (b)

atmospheric pressure; therefore, a seal is necessary between the two. This seal consists of two carbon packing rings *s* that fit the shaft very closely, but do not bear against it with any pressure. As a further preventive, steam at slightly above atmospheric pressure is admitted through pipe *t*. The pressure around the packing rings being higher than in chamber *r* causes a very small flow of steam into the pan *u*, thereby preventing a flow of air in the opposite direction. All condensation is thrown by deflector *v* into the pan *u* and drained away. The set has two additional guide bearings, one between the turbine and the generator and the other above the generator; both are supplied with oil under pressure.

67. Bearings for Horizontal-Shaft Steam-Turbine Alternators.—In order to keep the bearings of large hori-

zontal turbo-alternators cool, special arrangements are essential. In some cases, oil is circulated through the bearings under pressure and also through separate cooling coils before returning it to the bearings; another plan is to circulate cooling water through pipes embedded in the bearing metal below the shaft, as shown in Fig. 49. In (*a*) is shown a cross-sectional view at the center of the lower half of the bearing, and in (*b*) is a development showing the arrangement of the cooling pipes before the bearing metal is poured over them. The inlet and the outlet for the cooling system are shown at *a* and *b*, view (*a*), and the sections of the pipes themselves can be seen at *c*. Oil enters the bearing under pressure at the opening *d*.

VENTILATION

68. The losses per kilowatt output are practically the same in the steam turbo-alternator as in others, but the output is so

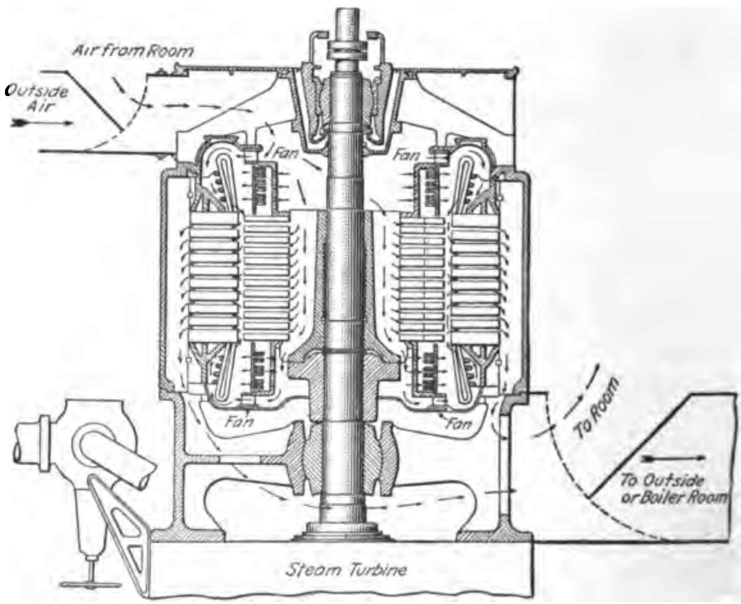


FIG. 50

much greater in proportion to dimensions that the losses per unit cubical contents are very high. Moreover, little space is

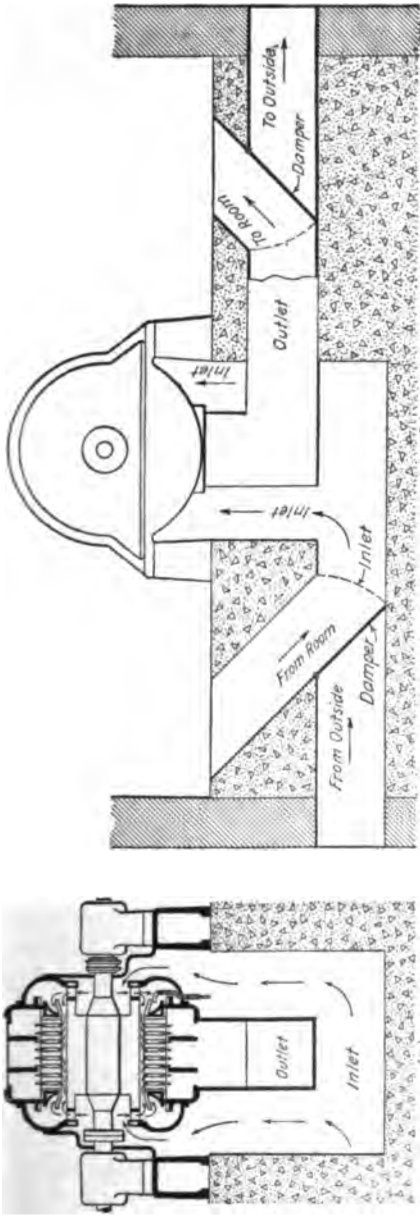


Fig. 51

available in the turbo-alternator for ventilation. Special means are therefore essential for circulating air.

69. Vertical Turbo-Alternators.—Fig. 50 shows, by arrows, the circulation of air through a vertical turbine-driven alternator. By means of dampers, air can be taken in above the alternator either from outdoors or from the dynamo room, and, after passing through the machine, it can be discharged into the room if heat is needed or it can be diverted into the boiler room or outdoors. Fans at the ends of the rotating field cause air to circulate, as shown, through openings and ducts in the windings and cores so as to carry away the heat. The field construction of this particular alternator, with the fans removed, is shown in Figs. 41 and 42.

70. Horizontal Turbo-Alternators.—A general scheme for ventilating a horizontal turbine is shown in Fig. 51, in

which (*a*) is a section in a plane of the shaft, and (*b*) a cross-section. View (*a*) shows, by arrows, the general circulation through the parts of the machine, and view (*b*) the possible sources and outlets of air for ventilation.

Fig. 52 shows more clearly how the air is made to circulate through the windings and the armature core of the machine for which the rotating field is shown in Fig. 44. Air enters from below the machine, as shown in Fig. 51; a small part of it passes through the grooves *a*, Fig. 52, near the rotor body and out through the coil ends and the holes in the protecting plates, where it joins the main current that has entered through the fans *b*. The arrows indicate the path through the air gap and the ducts in the stator core into the space inside the alternator casing, whence the discharge circulates around the machine and out at the bottom, as shown in Fig. 51. Holes are sometimes provided in the casing for discharging heated air directly into the engine room, although additional heat in the engine room is rarely necessary.

A salient-pole rotor, Fig. 47, acts as a fan; but it is usually equipped with axial fans to impel air into the spaces between the poles, whence it passes through the stator practically as shown in Fig. 52.

71. Air Supply.—For safe operation, the quantity of air should range from about 5 cubic feet per kilovolt-ampere output for ventilating small turbo-alternators to 2.5 cubic feet per kilovolt-ampere for large machines. At this rate of supply, the temperature of the air will be raised about 20° C. (36° F.) in the machine. For example, a 500-kilovolt-ampere machine requires approximately 2,500 cubic feet of air per minute, while a 25,000-kilovolt-ampere machine requires approximately 60,000 cubic feet.

The entering air should be cool and clean; a small percentage of moisture does no harm and does practically no good, although it may carry off a trifle more heat per cubic foot than dry air. The cooler the air entering the alternator, the lower will be the operating temperature of the machine or the higher will be the output for a given temperature.

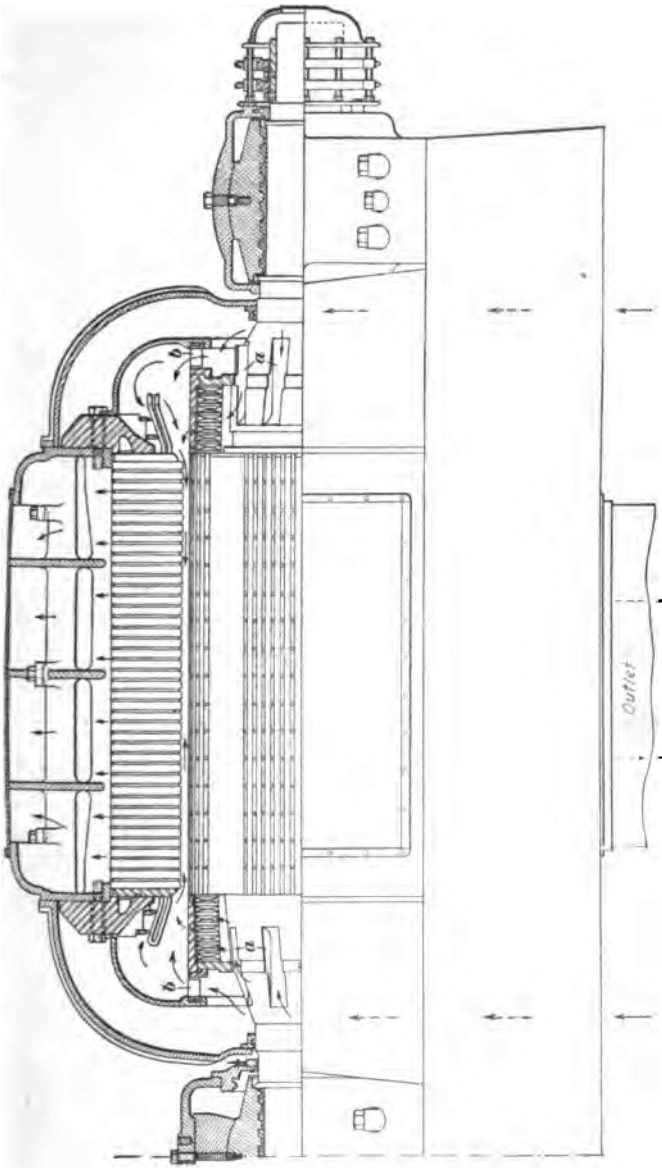


FIG. 52

72. Cleanliness of the air supply is very important. The presence of dust in the air causes deposits in the air passages, especially if the air also contains oil vapor. Air should therefore not be taken from a room in which reciprocating engines are operating, because the method of lubricating such engines produces oil vapor. The practice of taking air from outside the room in which steam turbo-alternators are operating is preferable and is general; discharging it oustide is also quite common. The air thus obtained is cleaner and cooler than if taken and discharged inside, and the noise is greatly reduced.

73. Cleaning and cooling devices, called *humidifiers*, are available. By means of these devices the incoming air is passed through a spray of water and through a cloth filter, on which the dust is washed away, leaving the air clean, cool, and free from water particles. The usefulness of such devices is most marked where the incoming air is hot and dusty.

CONNECTIONS OF ALTERNATOR WINDINGS

FIELD CONNECTIONS

74. The field coils of an alternator are connected similarly to those of a direct-current generator, so that alternate poles shall have alternate polarity. Fig. 1 indicates the field connections of an alternator with rotating armature; the connections of a rotating field differ only in bringing the leads along the shaft to the collector rings, as at *k*, Fig. 29.

ARMATURE CONNECTIONS

75. Two-Phase Chart.—When removing windings from any electrical machine with the intention of replacing them, accurate records of connections should be made as a guide. If the desired connections of the armature of an alternator cannot be determined from the old windings, a chart should be

constructed and followed in making the new connections. The method of constructing this chart can be best explained by assuming a typical case and describing the chart construction.

Assume, for example, that a 24-slot stationary armature with two bars per slot is to be connected for two-phase output with a four-pole field. The number of slots per pole is six and

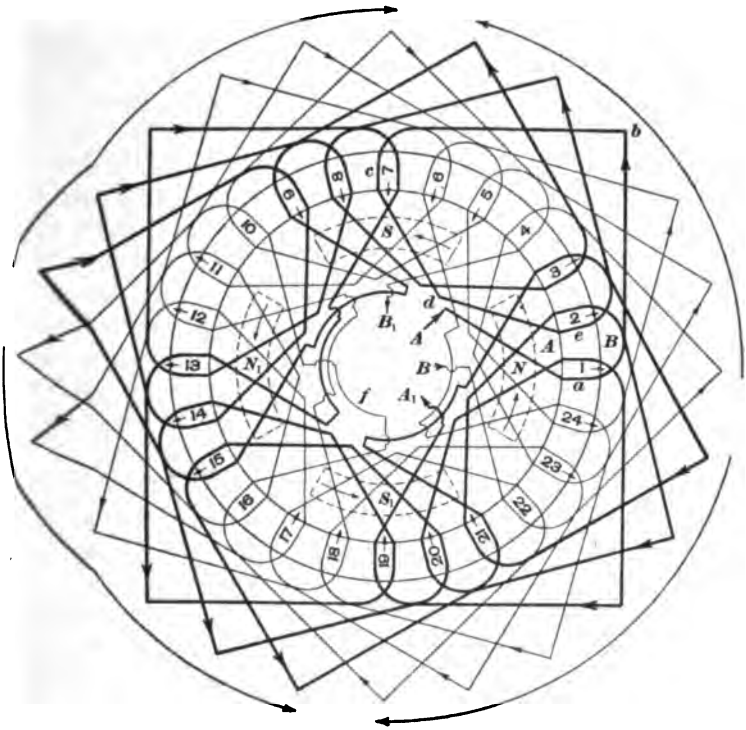


FIG. 53

the number per phase per pole three. Each bar has a terminal at each end, and these terminals must be connected with corresponding terminals of other bars or with the external circuit so as to give the correct voltage and phase relations.

76. This armature core would have the general appearance of that shown in Fig. 4, though with fewer slots. Suppose a circle A, Fig. 53, represents one end of the inner cylindrical

surface of the armature and a circle B represents the other end. For convenience, call A the rear end and B the front end. Let all the rear-end connections be represented inside circle A and all the front-end connections outside circle B, and let the slot conductors be represented by short lines between the two circles, the two bars in each slot being represented by parallel lines; in reality, one conductor lies over the other in the slot. For convenience, the slots are numbered consecutively, beginning with any slot.

An instantaneous position of the rotating field can be indicated by dotted lines representing poles N, S, N_1, and S_1. At the instant indicated, conductors in slots *23*, *24*, *1*, *2*, and *3* lie in the field of pole N; those in slots *5* to *9*, inclusive, in the field of pole S; those in slots *11* to *15*, in the field of pole N_1; and those in slots *17* to *21*, in the field of pole S_1. The conductors in slots *1*, *7*, *13*, and *19*, being opposite the centers of pole faces, are cutting lines of force at the most rapid rate and hence generating highest instantaneous voltages. The voltage generated in slot *7* is directly opposite in phase to that generated in slot *1*, or 180 electrical degrees from it, because one is opposite the center of a south pole and the other opposite the center of a north pole. Between these two slots are six equal slot spaces, and the phase difference between the voltages generated in adjacent slots is therefore $180 \div 6 = 30$ electrical degrees. On tracing counter-clockwise around the diagram, it will be seen that the first conductor in each slot is a top conductor and the second is a bottom conductor. For instance, conductor *a* in slot *1* is a top, and conductor *c* in slot *7* is a bottom conductor.

77. A diagram such as that shown in Fig. 54 is now drawn to show the phase relations of the voltages in the slot conductors. Conductors in slots *1* and *13*, lying opposite centers of north poles, generate voltages in the same direction across the stator face, and this direction is represented by the arrow *1–13*. Conductors in slots *7* and *19*, lying opposite centers of south poles, generate voltage in a direction opposite, or 180 electrical degrees, from that of the voltage generated in slots *1* and *13*; this direction is therefore represented by the arrow *7–19*. The

voltages generated in other conductors are also represented by arrows drawn to represent the correct phase relation. For example, in slots *2* and *14* the voltage is 30 electrical degrees from that in slots *1* and *13*, and the arrows *1–13* and *2–14* are drawn to represent this angle; the voltages in slots *3* and *15* are 30 electrical degrees from those in *2* and *14*, etc.

78. After Fig. 54 is completed, the end connections can be represented in Fig. 53. The front terminal of a conductor in slot *1* must be connected with the front terminal of a conductor in which the direction of the voltage is opposite, in order that the voltage in one conductor *forward* across the armature face shall be added to that in the other conductor *backward* across the armature face. According to Fig. 54, conductors in slots *7* and *19* answer this requirement, and either could be used. Assume that slot *7* is selected; then connecting lines *abc*, Fig. 53, are drawn, giving counter-clockwise progression of the winding. This selection is purely arbitrary. All the lines representing front-end connections can now be drawn symmetrically with lines *a b c*, connecting conductors in slots *2* and *8*, *3* and *9*, etc.

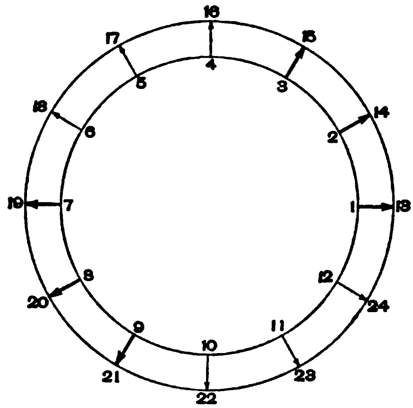


FIG. 54

At the rear, the slot conductors must be connected in groups of three, because there are three slots per phase per pole. Bottom conductor *c* in slot *7* must be connected to a top conductor in a slot whose voltage is as nearly as possible 180° displaced. According to Fig. 54, the voltage in slot *2* or *14* is displaced 150°, and up to this point the top conductors in both these slots are unused. Slot *2* gives a lap winding (Art. **19**) and slot *14* gives a wave winding (Art. **20**), as can be seen by noting the positions of these slots on Fig. 53. By selecting

slot *2* and drawing lines *c d*, *d e* and corresponding lines connecting the rear ends of conductors in slots *8* and *3*, the rear connections of one group of conductors are completed. This group traced in series is *1–7*, *2–8*, *3–9*, and these conductors are joined so that their voltages are added, as is shown in Fig. 54.

79. Winding Units and Winding Pitch.—A complete loop, or turn, as *A a b c d*, Fig. 53, is called a *winding unit*, or coil (see Fig. 8). The distance between the two sides of a winding unit is the *winding pitch*. If this distance in slots equals the number of slots per pole, the winding is called a *full-pitch winding;* if less than the number of slots per pole, it is a *fractional-pitch winding*.

The winding represented in Fig. 53 is a full-pitch winding. By tracing the circuit through the three winding units for which rear connections have been described, it will be seen that the slots traversed successively from phase terminal *A* at the rear are *1–7–2–8–3–9*, terminating this group at the rear. This rear terminal of the conductor in slot *9* must be connected, according to Fig. 54, with a conductor in slot *15*, requiring one of the pole connectors referred to in Art. **31** and shown in Fig. 20 (*d*). According to both Figs. 53 and 54, the other terminal from the rear of slot *9* should be connected with a terminal from slot *14*, the remaining terminal from slot *8* with a terminal from slot *13*, thus completing the second group of three winding units through slots *15–9–14–8–13–7*.

According to Fig. 54, the remaining rear terminal from slot *7* should be connected with slot *13*, and another group completed through slots *13–19–14–20–15–21*. The remaining rear terminal from slot *21* should connect with slot *3*, and the fourth and last group of three units in this phase completed through slots *3–21–2–20–1–19*. Terminals *A* from slot *1* and A_1 from slot *19* are the terminals of what may be called phase *A*; this phase is indicated in Figs. 53 and 54 by heavy lines.

Phase *B* must be so connected as to generate voltage 90 electrical degrees from the voltage in phase *A*. According to Fig. 54, phase *B* should therefore begin in one of four slots *4*, *16*, *10*, or *22*. If slot *4* is chosen and reference is made to

Fig. 54 to determine proper phase relations of slot conductors, the connections of phase B may be completed in four groups, as follows: *4-10-5-11-6-12*, *18-12-17-11-16-10*, *16-22-17-23-18-24*, *6-24-5-23-4-22*. The phase terminals are B_1 and B. This completes a symmetrical chart, Fig. 53, which can be followed when connecting the winding.

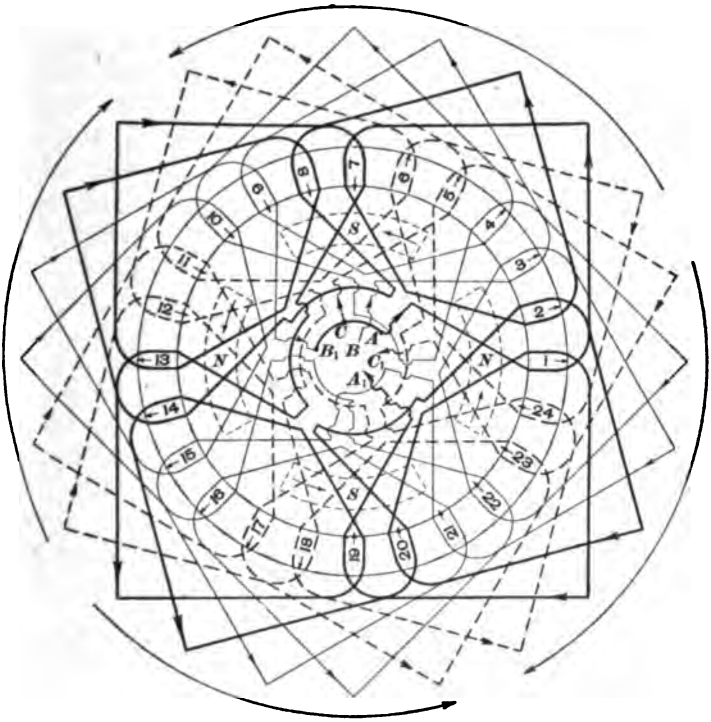


FIG. 55

80. The directions of currents in the units at the instant represented are as indicated by the arrowheads on the lines representing front-end connections, and the general directions through the several groups are as indicated by the long curved arrows outside the chart. These directions can be verified by noting that the electromotive forces generated in the conductors are from rear to front opposite north poles and from front to rear opposite south poles.

81. Three-Phase Connections.—In Fig. 55 is shown a chart for connecting a full-pitch winding to deliver three-phase current. This chart is constructed by the aid of the phase diagram shown in Fig. 56. Its construction is the same as described for the two-phase chart, with the exception of the representation of the rear-end connections. In this case, there are two slots and two winding units per phase per pole, or four groups of two units each per phase.

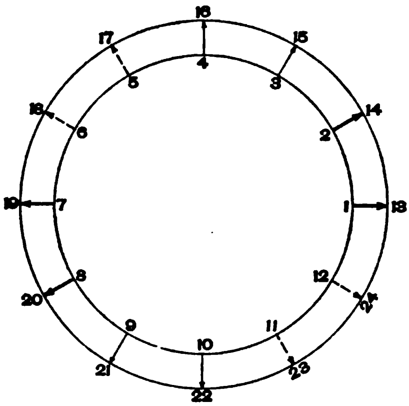


FIG. 56

By referring to both Figs. 55 and 56 and connecting the rear terminals so that the electromotive forces shall be in the same general direction, a rear terminal from slot *7* is connected with a terminal from slot *2*, completing one group of phase A, beginning with rear terminal A through slots *1–7–2–8*. According to Fig. 56, one rear terminal from slot *8* can be connected with a terminal from slot *14* and the other with slot *13*, completing the second group through slots *14–8–13–7*. Connecting together the remaining rear terminals from slots *7* and *13* and the remaining terminal from slot *14* with a terminal from slot *19* completes the third group through slots *13–19–14–20*. The rear terminals from slot *20* are connected with the remaining rear terminals from slots *2* and *1*, completing the last group of the phase through slots *2–20–1–19* and ending the phase in rear terminal A_1 from slot *19*.

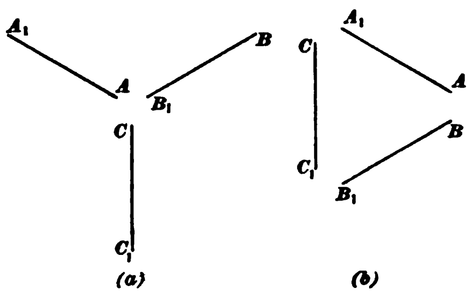


FIG. 57

The connections of the other two phases are represented in a similar manner. The conductors must be so placed that the three voltages shall be 120 electrical degrees apart. According to Fig. 56, the proper phase relations are obtained by beginning the three phases in slots *1*, *5*, and *9*, which are the slots chosen in constructing the chart, Fig. 55; the three phases thus end in terminals from slots *19*, *23*, and *3*.

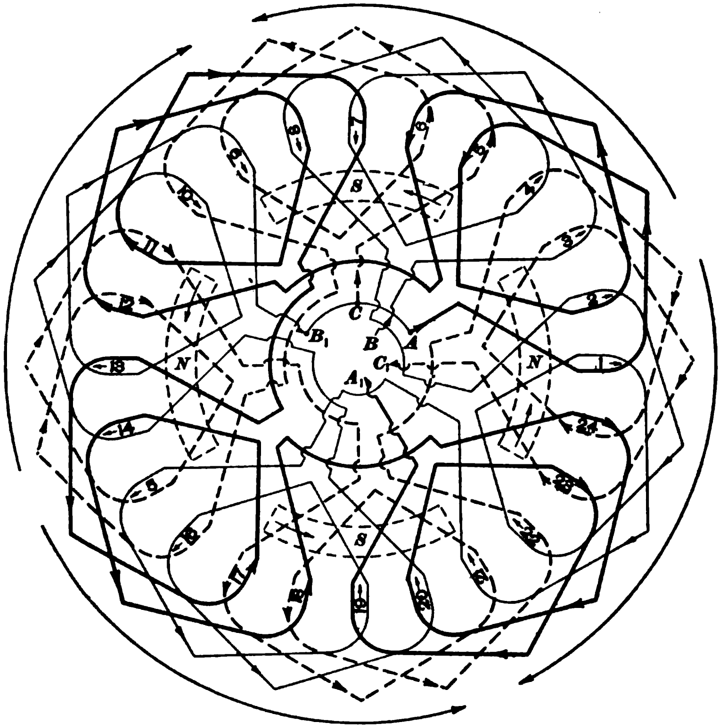


FIG. 58

82. The three phases can then be connected in star **Y** or in delta Δ, as indicated in Fig. 57. Each phase is here represented by a straight line with letters corresponding to those used in Fig. 55. For star-connection terminals, A, B_1, and C are joined as in Fig. 55 and as indicated in Fig. 57 (a); for delta-connection terminals, A_1 is joined to C, A to B, and B_1 to C_1, as indicated in Fig. 57 (b). Fig. 55 shows **Y** connection.

83. Fractional-Pitch Winding.—Fig. 58 shows a chart for a fractional-pitch, three-phase, Y-connected winding, and Fig. 59, the time-phase diagram by the aid of which the chart is made. The winding units span only four slots or two-thirds of full pitch, thus including only a part of the flux. This winding gives lower voltage than a full-pitch winding, but is sometimes more desirable on large machines having few poles, because of shorter end connections.

In the construction of the chart, Fig. 58, a terminal issuing from the front of a slot numbered *1* is indicated as connecting with a terminal from slot *5*, and all other front connections are drawn symmetrically with this one.

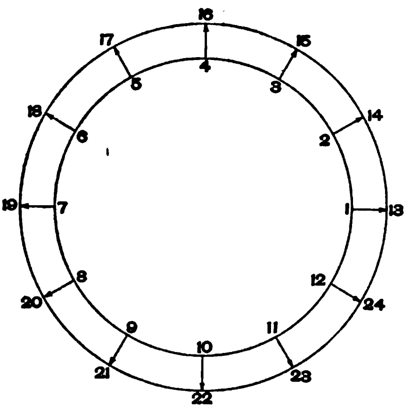


FIG. 59

84. In making the rear-end connections, according to Fig. 59, they are joined so that the circuit of one phase, beginning with terminal A, Fig. 58, can be traced in four groups through the following slots: *1–5–2–6*, *12–8–11–7*, *13–17–14–18*, *24–20–23–19*, ending in terminal A_1. The connections of the other two phases, terminating at $B\ B_1$ and $C\ C_1$ are similarly drawn. The three phases can be Δ-connected in the manner as described in Art. **82**.

85. Charts for connections with any number of slots can be drawn on the same general plan. In every case the connections should be symmetrical; that is, the choice made where more than one way is available should be adhered to consistently. The winding units and the connections should be so made that in each case a terminal from the bottom of a slot connects with a terminal from the top of a slot. The connections at both ends of the armature should be so arranged that all terminals from bottoms of slots extend one way and all terminals from tops of slots extend the other way.

TRANSFORMERS

GENERAL DESCRIPTION

FUNDAMENTAL PRINCIPLES

1. A **transformer** is a device used on alternating-current circuits to change high-voltage energy into low-voltage energy, or vice versa. The action of the transformer is based on the fact that if the current varies in one of the two coils, say *a*, Fig. 1, wound on a magnetic core, an electromotive force is induced in the other coil *b*.

The coil supplied with current is called the *primary*, and the other coil in which the voltage is induced, due to the variation of the current in the primary, the *secondary*. Either of the two coils may be made the primary or the secondary, depending on which is connected to the source.

2. Further, the voltages applied and induced bear the same relation to each other as the number of turns of the primary bears to the number of turns of the secondary. For example, if the secondary has one-third as many turns as the primary, the induced voltage will be one-third of the applied voltage; if the secondary has three times as many turns as the primary the induced voltage will be three times the applied voltage.

With current in the secondary coil, a current must also exist in the primary coil; and the two currents are always of such values that the product of the secondary current and the secondary voltage is approximately equal to the product of

the primary current and the primary voltage. These conditions would exist in an ideal transformer, that is, one having no losses; but all commercial transformers have some losses due to resistance, hysteresis, etc. that modify the ideal conditions to some extent.

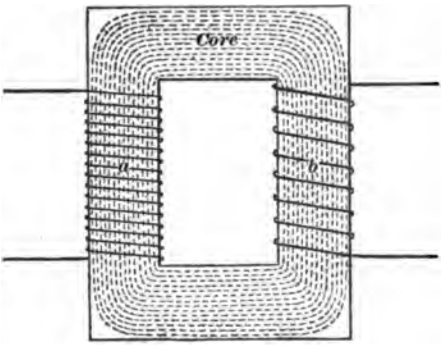


FIG. 1

3. General Formulas.—The essential parts of a transformer, as represented by Fig. 1, are a rectangular iron core, forming a magnetic circuit, and two coiled conductors *a* and *b* interlinked by this circuit. When one of the coils, say *a*, is connected with a source of alternating voltage, this coil becomes the primary and receives from the source a *magnetizing*, or *exciting*, current, which causes alternating flux in the core. This flux interlinks both coils and induces in them electromotive forces as follows:

$$E_p = \frac{4.44\ \Phi N_p f}{10^8}, \qquad (1)$$

and

$$E_s = \frac{4.44\ \Phi N_s f}{10^8}, \qquad (2)$$

in which E_p = effective value of induced electromotive force in the primary;
E_s = effective value of induced electromotive force in the secondary;
N_p = number of turns on the primary;
N_s = number of turns on the secondary;
Φ = maximum value of the flux;
f = frequency, in cycles per second.

If formula 1 is divided by formula 2, member by member,

$$\frac{E_p}{E_s} = \frac{4.44\ \Phi N_p f}{10^8} \times \frac{10^8}{4.44\ \Phi N_s f} = \frac{N_p}{N_s} \qquad (3)$$

The ratio of induced voltages in the windings is thus shown to be equal to the ratio of the number of turns. Formula **3** shows that from any alternating voltage any desired voltage can be obtained by means of a magentic circuit interlinking two windings with turns proportional to the two voltages. The formulas given are for an ideal transformer, the losses not being taken into consideration.

4. The voltage induced in the primary, that is, the counter electromotive force, is practically equal to the applied voltage, and is 180 time-degrees from it in phase. These two voltages are considered equal, although the very small loss in overcoming resistance by the magnetizing current makes the induced voltage a trifle less than the applied voltage.

The value of the magnetizing current depends on the value of the flux that it must establish. If the magnetic circuit is of a comparatively high reluctance, for example if it is long and of small cross-sectional area or is made up of poor magnetic material, a larger magnetizing current will be required to establish the required flux than if the circuit were of large cross-section and of good magnetic material.

5. Influence of Current in Secondary.—Current resulting from induced voltage in the secondary, in other words the *induced current*, is 180 time-degrees behind the primary current, and this induced current in turn induces flux opposing that established by the primary current. The primary current therefore increases enough to overcome the demagnetizing effect of the secondary current, this increase being known as the *load current*.

The magnetomotive force due to a given current in a coil is proportional to the product of the current and the number of turns in the coil, or the *ampere-turns*. Therefore, in order to nullify the secondary magnetomotive force by the magnetomotive force due to the current in the primary coil, these magnetomotive forces must be equal and opposite.

Let F_s = magnetomotive force of the secondary coil;
F_p = magnetomotive force of the primary coil;
F_m = part of F_p necessary for magnetizing the core.

Then, $$F_s = F_p - F_m$$

At full load, the value F_m can be neglected, because it is so small a proportion of the total, leaving as approximately true the formula,

$$F_s = F_p$$

6. If the secondary ampere-turns were not entirely neutralized by an equal number of primary ampere-turns, the secondary current would cause a change in the core flux, and the induced counter electromotive force in the primary would no longer be equal to the applied voltage. This difference in the applied and induced voltages would act on the primary coil, increasing the primary current. Equilibrium would be reached only when the induced and applied voltages were equal; that is, when the secondary ampere-turns were neutralized by an equal number of primary ampere-turns produced by a current in the primary in addition to the exciting current.

In most transformers, the exciting current is small compared with the full-load current; therefore, very little error is introduced by assuming that the ampere-turns of the primary are equal to the ampere-turns of the secondary.

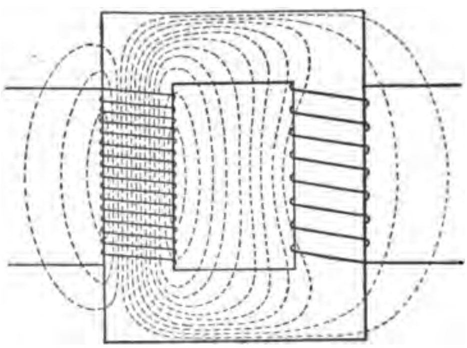


FIG. 2

7. Influence of Magnetic Leakage. In a practical transformer, the ratio $\frac{E_p}{E_s}$ is somewhat greater than the ratio $\frac{N_p}{N_s}$ because of the fact that some of the flux interlinking with the primary passes, or leaks, through the space between the two windings, as shown in Fig. 2, without interlinking the secondary.

At no load, this leakage flux is negligible, because the magnetic circuit offers a very much better path for the flux than the surrounding space. But with load, the primary and secondary

ampere-turns being opposed to each other, are jointly effective in producing an appreciable leakage flux. The reluctance of the air path being constant, the amount of leakage flux is directly proportional to the current in the windings. The flux interlinking both primary and secondary windings may be called *useful flux* in distinction from the leakage flux that interlinks the primary winding only. The induced voltage in the primary is therefore made up of a voltage induced by the useful flux and a voltage induced by the leakage flux. The latter voltage is called the *reactance volts*, or *reactance drop*, in the transformer.

8. Influence of Resistance of Windings.—When the transformer is loaded, a small part of the primary voltage is consumed in overcoming the resistance of the primary winding. This causes the induced counter electromotive force of the primary to be slightly smaller than the applied voltage. Similarly, the voltage induced in the secondary is always larger than the terminal voltage of the secondary windings, on account of the resistance of the secondary windings. If the load of the secondary is non-inductive, the voltage drops due to resistance are in phase with the terminal voltages; therefore, the primary induced voltage can be determined by subtracting arithmetically the primary resistance drop from the applied voltage, and the induced secondary voltage can be obtained by adding arithmetically the secondary resistance drop to the secondary terminal voltage. If the load is inductive, proper consideration must be given to the phase angle. In well-designed transformers, the resistance drop in each winding is from ½ to 1 per cent. of the normal induced voltage.

STRUCTURAL FEATURES

TWO-COIL TRANSFORMERS

9. Transformers may be classed roughly as *two-coil* and *single-coil* types, the latter being more generally called *autotransformers*. The general principles and many of the structural features are the same for both types. The word *transformers* nearly always refers to the two-coil type; the distinctive features of autotransformers will be described under a separate head. According to the shape of their cores, transformers may be classed as *core type*, *shell type*, and *distributed core* type.

10. The **core-type transformer** consists of a single magnetic circuit of

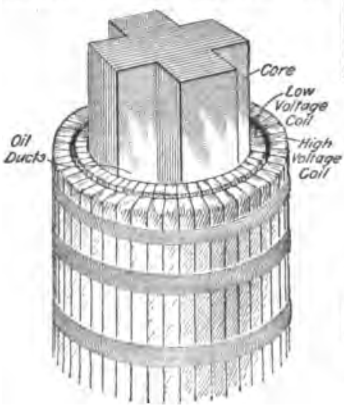


FIG. 3

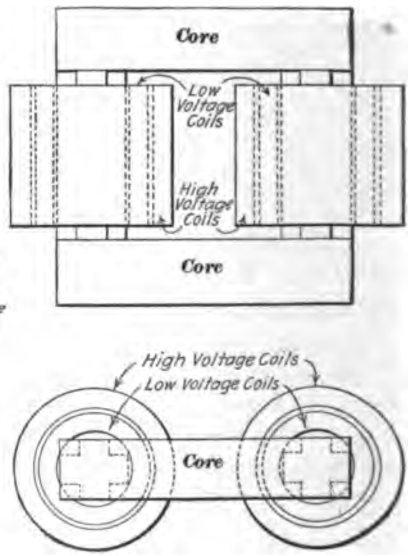


FIG. 4

square, rectangular, or cruciform cross-section, with a rectangular opening, or *window*, to accommodate the windings. Fig. 3 shows one leg of a transformer of which the core has a cruciform cross-section.

The windings, which are usually of cylindrical shape, are placed on the two legs of the magnetic circuit, surrounding them

entirely. Relative positions of the windings and core are shown in Fig. 4. The low-voltage coils, unless large and heavy connections prevent, are usually placed next to the core, and the high-voltage coils are external and concentric with them.

A transformer of this type is shown in Fig. 5. The high-voltage windings are outside and separated from the low-

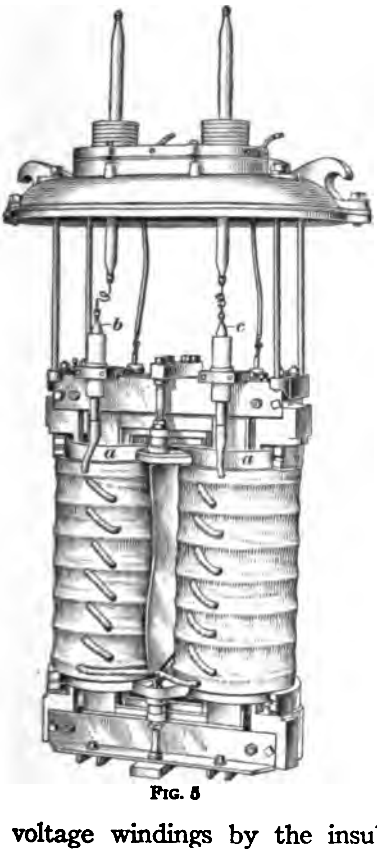


FIG. 5

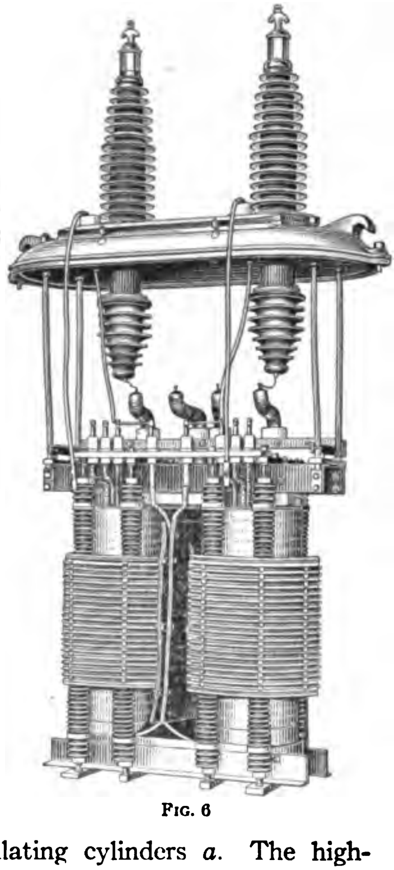


FIG. 6

voltage windings by the insulating cylinders *a*. The high-tension winding consists of several form-wound coils, all of which are taped together and connected in series. As viewed from above, the conductor connected to terminal *b* passes through the window in a counter-clockwise direction and winds in many turns around that leg of the core. The last turn con-

nects to the bottom turn on the other leg, and the turns are wound on this leg clockwise, ending finally in the terminal *c*.

In this manner, all the turns act together in magnetizing the core in one direction. The secondary connections are made on the other side of the transformer, the coils consisting of a heavy conductor wound around each leg.

The high-voltage winding of the transformer shown in Fig. 6 is composed of several disk-shaped coils and is called the *disk-type winding*. Each coil is wound spirally with one turn per layer, being spaced from its neighbors by insulating strips so as to provide horizontal oil ducts. This particular transformer is insulated for 115,000-volt service.

The core-type construction is usually employed in the United States on moderate and high-voltage transformers of capacities ranging from 100 to 2,000 kilovolt-amperes. Foreign practice in some cases employs this type on capacities even as great as 3,000 and 4,000 kilovolt-amperes.

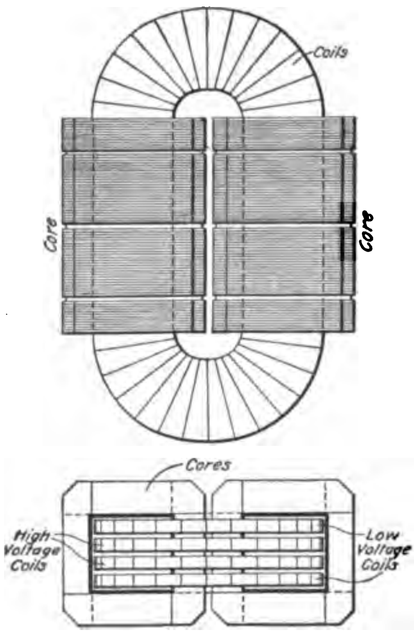


FIG. 7

11. The shell-type transformer, Fig. 7, is distinguished by a divided magnetic circuit, all coils being on one leg. The middle leg is usually divided, as shown, virtually making two core-type magnetic circuits in multiple, but it is sometimes constructed of sheets cut the full width of the leg.

The windings on the shell-type transformer are usually of so-called *pancake* construction, shown in Fig. 8, the groups of high- and low-voltage coils being alternated in order to reduce the reactance. In the pancake windings, the conductor

is usually wound spirally to the required number of turns per section, two of these spirals, or sections, being assembled as one coil with an insulating collar separating the sections. The shell-type construction is usually employed on large transformers, and wherever heavy currents are required. A good idea of the construction of a large shell-type transformer is obtained from Fig. 9. The assembled primary and secondary coils are ***boxed in*** with insulation, and the surrounding magnetic

FIG. 8

circuit is being laid up sheet by sheet. A view of the assembled transformer without the tank is shown in Fig. 10.

12. In the **distributed-core transformer,** the magnetic circuit usually consists of a five-legged structure, as is shown in Fig. 11. The coils are assembled concentrically on the central leg, the outer four legs being uniformly disposed outside of the windings. There are thus four magnetic circuits in multiple. The construction and location of high- and low-voltage coils are generally the same as in core-type transformers. The distributed-core construction is usually employed on small

low-voltage transformers, say, up to 100 kilovolt-amperes. Fig. 12 shows the most common form of this transformer.

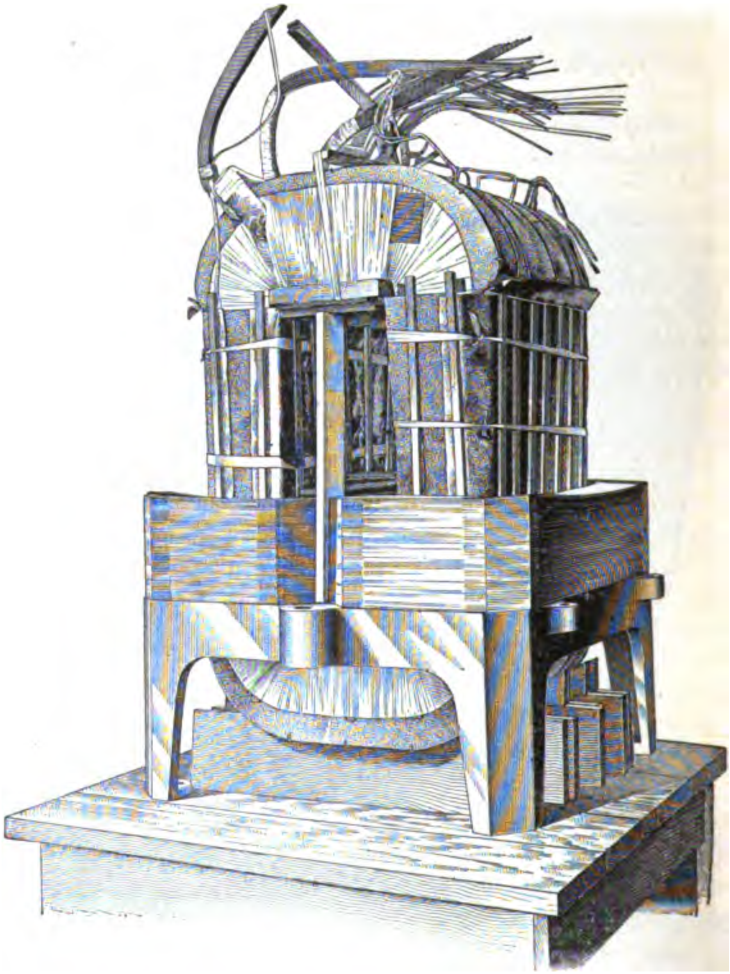


FIG. 9

13. A polyphase transformer, which is a combination of single-phase transformers into one two-phase or one three-phase unit, is sometimes used on a polyphase circuit instead of single-phase transformers.

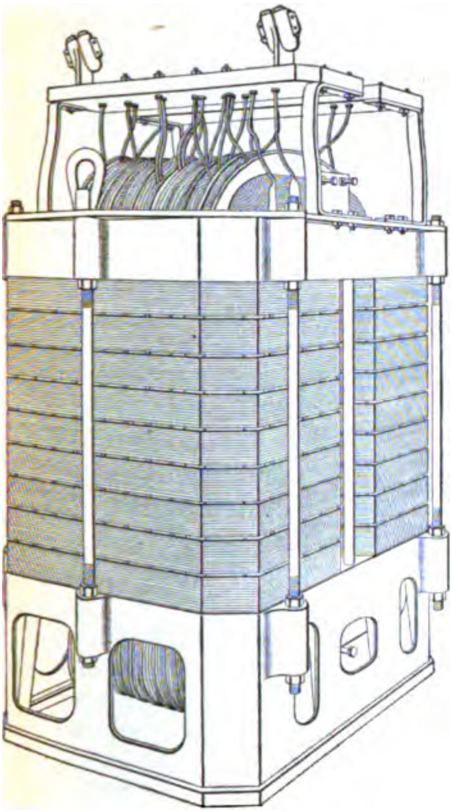


FIG. 10

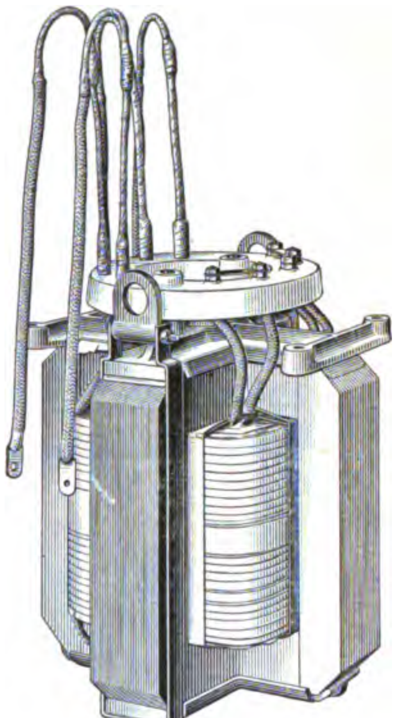
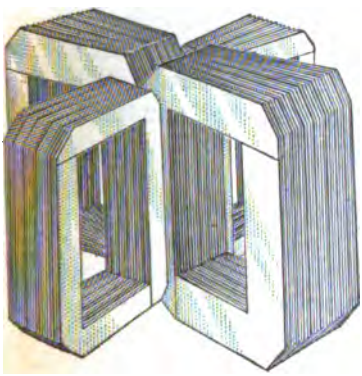


FIG. 12



11 FIG. 11

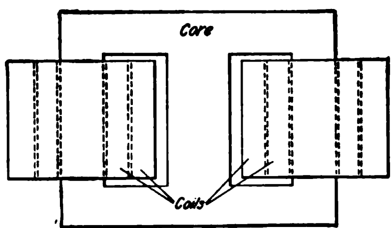


FIG. 13

14. The **two-phase unit** is rather uncommon, as it is customary to employ two single-phase transformers for commercial two-phase work. The magnetic circuit of a two-phase, core-type transformer is shown in Fig. 13. This circuit is of precisely the same form as that of a single-phase shell-type transformer. In that case, however, two outer legs serve simply as parallel paths for the flux, while in a two-phase unit each outer leg carries a flux differing in phase by 90 time-degrees from the flux in the other. The middle leg serves as a return path for these fluxes, and as their resultant is 1.41 times greater than either of the two fluxes, the cross-sectional area of the middle leg must be 1.41 times greater than that of either outer leg.

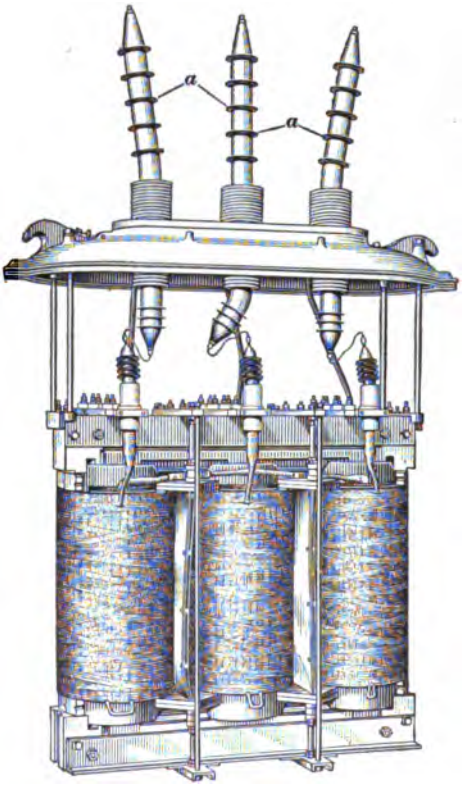


FIG. 14

15. The **three-phase transformer** is a highly efficient combination of three single-phase units.

In Fig. 14 is shown a view of a core-type, three-phase transformer without its tank. The magnetic circuit consists of three equal legs that are joined at the top and the bottom, as shown in Fig. 15. The legs *a*, *b*, and *c* carry three fluxes differing in phase 120 time-degrees. Since the vector sum of three fluxes 120 time-degrees apart is zero, no return circuit is required.

Three-phase transformers are of either the shell or the core type. Three-phase, distributed-core transformers have been built commercially, but they consist merely of three single-phase units placed one over the other and mounted as one unit in the tank.

16. Advantages and Disadvantages of Polyphase Transformers.—Owing to the fact that the different magnetic circuits of two- or three-phase transformers are partly combined, a polyphase transformer of a given kilovolt-ampere capacity employs less material and occupies less floor space than three single-phase transformers of the same combined kilovolt-ampere capacity. Moreover, the cost and weight of the polyphase unit is generally less than its equivalent capacity in single-phase transformers.

Because of the fact, however, that in case of breakdown on one of the phases, the cost of repairs is greater for the polyphase unit than for one of the single-phase units, and that the cost of a spare polyphase unit is greater than that of one of the single-phase units, the tendency has been to discredit the use of polyphase transformers. However, the art of transformer manufacture has now advanced to the point where there is so little likelihood of breakdown under ordinary conditions that such argument has very little weight. As a result, the polyphase transformer is used more and more extensively.

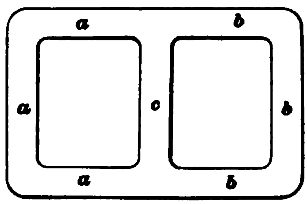


Fig. 15

17. Features Common to All Types.—From the foregoing descriptions, it may be summed up that the terms core type, shell type, and distributed core refer to the arrangement of the magnetic circuit. In the core type, the magnetic circuit forms a core to the coils; in the shell type, it forms both a core and a protecting shell to the coils; in the distributed-core type, the core is distributed around the coils.

In the assembly of the three types of cores, the general practice is to lay up the laminations so as to give lapped joints at

the corners. However, the use of butt-jointed cores is common in foreign practice, and is being employed here and there in the United States. Butt joints require very careful assembly and rigid clamping in order to prevent chattering, or buzzing, of the laminations.

On all types, high- and low-voltage windings are carefully insulated from each other by the use of heavy pads of varnished cloth, mica, and the like, and on all but the smaller sizes, additional insulation is secured through the use of ventilating ducts. It is particularly important that the insulation between high- and low-voltage coils have a high factor of safety, because, in case of failure, not only is the transformer put out of service, but the introduction of the high voltage to the load side where the devices are insulated for low voltages may involve loss of life. For this reason, in lighting transformer work, a test of at least 10,000 volts is applied between the coils, and when the line voltage is over 5,000 the test voltage is made twice the line voltage.

18. In addition to withstanding electrical stresses, the windings of a transformer are subjected to considerable mechanical stress when carrying current, owing to the electromagnetic repelling action set up by the currents in high- and low-voltage coils. The forces due to this action vary with the square of the current, and, consequently, under short-circuit conditions, are of very large magnitude. Unless the reactance in the circuit is sufficient to limit the current during short circuit to, say, ten to twenty times normal, these forces in large power transformers connected to big systems may amount to many tons and may result in the complete mechanical breakdown of the transformer, bending the coils and distorting them from their normal position.

Good practice demands very solid construction for the windings of a transformer. Before assembly, they are thorougly impregnated with a liquid insulating compound, which penetrates all parts of the windings, binding together the various turns and layers. This is accomplished by baking the coils in a tank from which the air is exhausted, then filling the

tank with hot insulating compound, and applying a pressure of from 75 to 100 pounds per square inch. The heat and the vacuum remove the moisture and air from the coils, and the pressure then forces the liquid compound into all the cores and crevices, where it hardens on cooling and becomes a solid mass. This compound not only strengthens the coil mechanically, but it improves the insulation and helps to conduct heat away from the interior of the coil.

When assembled, the coils must be carefully centered on the cores and rigidly blocked in this position so as to prevent any movement under the stresses due to heavy currents.

AUTOTRANSFORMERS

19. An **autotransformer** is a transformer having only one coil with which both the primary and secondary circuits are connected. For example, in a single coil connected across a 200-volt circuit there is a counter voltage of 200 and in half of this winding there is a counter voltage of 100; therefore, between one side of the circuit and the middle point of the winding, as shown in Fig. 16, there is a voltage of 100. By thus eliminating the secondary winding, a large saving in copper results. For example, with a primary voltage of 200 and a secondary voltage of 100, 10 amperes in the secondary line and 5 in the primary are required to deliver 1 kilowatt. In the part a that carries only the primary current is 5 amperes, and in the part b is the difference between the load current of 10 amperes and the current in a, that is, 5 amperes. Therefore, each part of the winding must be designed to carry 5 amperes, whereas with a transformer having two windings, the secondary copper would be proportioned to carry 10 amperes.

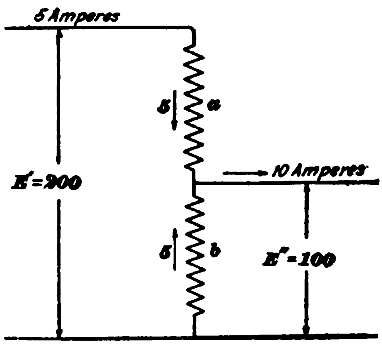


FIG. 16

20. Fig. 17 shows what the conditions would be if the secondary voltage were 150. The secondary current would then be 6.6 amperes for an output of 1 kilowatt; the primary current and the current in the part *a* of the transformer in series with the primary circuit would remain 5 amperes, leaving 1.6 amperes for the remaining part *b* of the autotransformer. The copper in part *b* of the winding could therefore be made of a considerably smaller cross-section than that in part *a*.

In general, the more nearly the ratio of transformation is to unity, the greater will be the saving of copper resulting from the use of one winding instead of two.

21. In a two-coil transformer, all the energy supplied to the primary winding is transformed into magnetic energy and then into electric energy in the secondary winding. In an autotransformer, only a part of the total energy is transformed, the rest of it being conducted directly to the secondary mains.

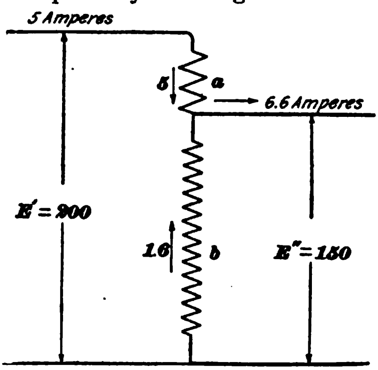


Fig. 17

Of the total energy delivered by the primary mains, the fraction $\frac{E''}{E'}$ is delivered directly to part *b*, Figs. 16 and 17, which, without transformation, transmits it to the secondary circuit. The remainder $\frac{E' - E''}{E'}$ is delivered to winding *a*, transformed by means of magnetic induction, and delivered to winding *b*, which transmits it to the secondary. Therefore, an autotransformer transforms only the part of the total power represented by the fraction $\frac{E' - E''}{E'}$. The part of the winding in series with the supply circuit, or part *a*, Figs. 16 and 17, is the primary winding, and the part *b* between the connections of the secondary circuit is the secondary winding. As in an ordinary transformer, the ampere-turns in these two parts are

equal and opposite. The smaller the part *a* of the winding, the smaller will be the energy transformed and the smaller will be the autotransformer for a given delivery of secondary power. Autotransformers, like two-coil transformers, can be used either to step up or to step down voltage.

LEADS

22. Transformer leads serve to connect the windings of the transformer to the line. On low-voltage units, the leads are made of a piece of flexible cable, which is brought out of overhanging covers fitted with porcelain bushings, as is shown later.

23. When the voltage exceeds 15,000 to 20,000, stiff leads are employed, and these pass out through the cover. For moderate voltages and indoor service, leads insulated with varnished cloth are often used, as in Fig. 5, in which the leads are shown projecting through porcelain bushings in the transformer cover. The distance over the surface of the lead between the high-tension connection and the tank is known as the *creepage distance*. If a discharge takes place, it is usually over this surface, and to guard against it, this distance is increased by insulating collars, as shown at *a*, Fig. 14. For outdoor service on moderate voltages, leads fixed in porcelain insulators are very widely used.

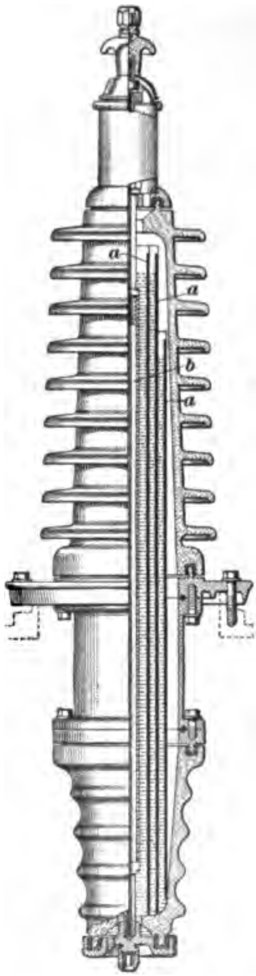


FIG. 18

24. When the voltage exceeds, say, 70,000, the conductor may be mounted in porcelain insulators filled with oil, as shown in Fig. 18, in which part of the terminal is cut away to show

the interior construction. The oil space is divided concentrically by thin insulating cylinders *a*. A metal rod *b* is used as the conductor and serves materially to strengthen the construction. The outer surface of the porcelain insulator is corrugated, or provided with flanges, called *petticoats*, in order to lengthen the creepage distance from the terminals to the tank, and the lead is provided at the top with an oil gauge having the proper oil level marked thereon.

FIG. 19

25. Another type of lead widely used for high-voltage work is the *condenser-type terminal*, shown in Figs. 19 and 20. The principle of this lead is that an alternating voltage applied to a number of condensers of equal capacity in series will be the same across each of the condensers, and will be equal to the total voltage divided by the number of condensers. Fig. 19 shows the appearance of the completed terminal, and Fig. 20 shows the construction.

In the condenser-type terminal, these condensers are built up as follows: On a metal rod *a*, Fig. 20, is rolled a layer of insulating material *b*, usually some specially impregnated paper; then, on this is rolled a sheet of tin-foil *c* of proper length, followed by another layer of the insulation, and so on until the proper number of condensers is obtained. As each condenser has a greater diameter than the one that precedes it, its length is shortened so that the capacities of all are as nearly equal as possible. This construction saves material, because every part of the insulation is subjected to approximately equal voltage stresses. If the insulation were solid without the tin-foil, the inner layer of insulating material would be subjected to greater voltage stress than the outer layer, and the terminal would

not withstand so high voltage as would a terminal with tin-foil. In testing two leads of the same material and the same diameter, except that the tin-foil was omitted from one, this one broke

FIG. 20

Section AB

down at 120,000 volts, while the other withstood voltages up to 230,000 before failing. The metal disk *a*, Fig. 19, with well-rounded corners helps to equalize the voltage stresses on the condensers.

OPERATION OF TRANSFORMERS

COOLING

26. When a transformer is connected with a supply circuit, heat is developed in the transformer core, owing to hysteresis and eddy-current losses. As the secondary current is increased, additional heat is developed, owing to copper losses in the windings. The maximum capacity of the transformer is the maximum load it can carry without developing heat enough to injure the insulating materials. This capacity can therefore be increased by employing means to cool the transformer. Among the means employed are *self-cooling, air cooling, oil cooling, oil-and-water cooling,* and *forced-oil cooling.*

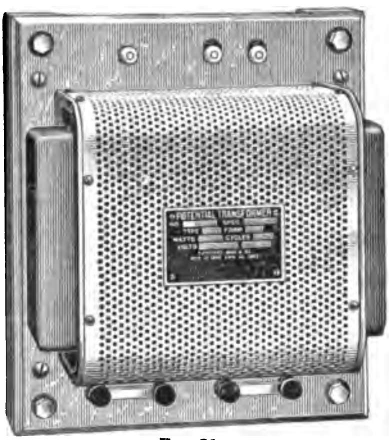


FIG. 21

27. Self-cooled transformers are those of small dimensions, as shown in Fig. 21, in which the ratio of surface to

volume is so large that no special means of cooling are considered necessary. Their cooling is effected by natural air-currents created by the difference in temperature of the windings and the surrounding air and by direct radiation.

As the size increases, the ratio of surface to volume constantly decreases. The total loss and, consequently, the heat to be dissipated are proportional to the volume of material; therefore, the surface per watt loss decreases as the size of the transformer increases. Artificial cooling becomes necessary in the larger sizes.

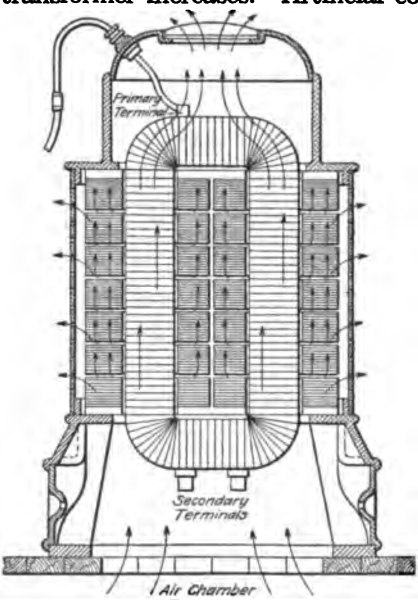


FIG. 22

28. In the **air-blast transformer,** which is generally of the shell type, the heat is carried away by air-currents forced through ducts in the windings and the core. Air-blast transformers are mostly used in large central stations in which the voltages do not exceed 35,000.

Fig. 22 shows a cross-sectional view, and Fig. 23 an external view, of such a transformer. Air at a pressure of ½ to 1½ ounces per square inch is forced up into the base by blowers, passing out of the top and also through horizontal core ducts and the perforated sides. The quantity of air may be regulated by means of dampers in the vent holes of the transformer top. Usually, 150 cubic feet of air per minute is sufficient for each kilowatt of loss.

Clean, dry air should be used, and, ordinarily, the difference in temperature between ingoing and outgoing air should not be over 25° C. In case of failure of air supply, it is not safe to run the transformer with load except for very short periods;

otherwise, the windings soon reach a dangerous temperature. For the same reason, an air-blast transformer cannot withstand a heavy overload except for short intervals. In ordinary service, the air ducts should be cleaned occasionally with compressed air to prevent clogging by dust; a pressure of 15 to 20 pounds per square inch will usually accomplish this.

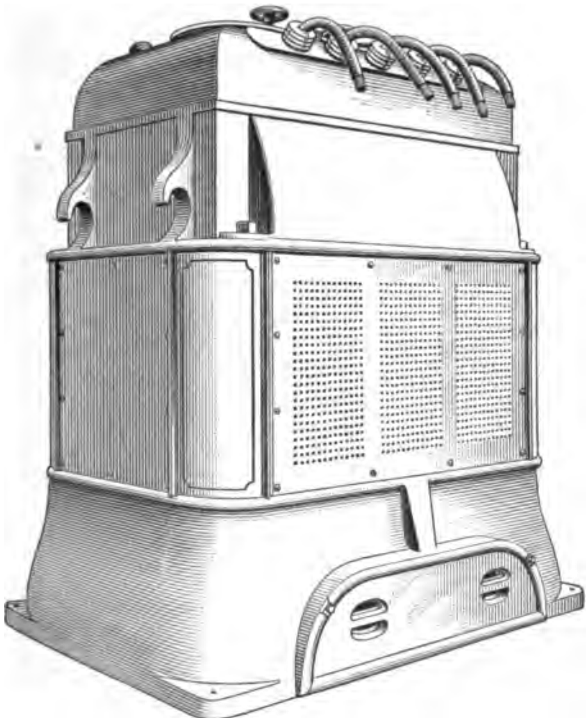


FIG. 23

29. Oil-cooled transformers are extensively used. The cores and coils of such devices are submerged in oil, which transfers heat from the windings to the outer tank. The oil next to coils is heated and, being lighter than cold oil, rises to the top, whence it circulates down the inner surface of the tank and is cooled. In addition to carrying away heat, the oil serves as an insulator between the various windings, and between the windings and the core. In fact, it would hardly

be possible to design a commercial, high-voltage transformer without the use of oil as an insulator.

30. Lighting transformers, Fig. 24, usually have a tank with a plain surface, this being sufficient to disperse the heat carried to it by the oil. As the size of transformer increases, the plain surface of the tank becomes insufficient, and the surface is increased by the use of radiating ribs on cast-iron tanks, or by corrugating the surface of sheet-steel tanks, as in Fig. 25. Tanks of the latter type are made for transformers of capacities as high as 1,000 kilovolt-amperes; the seams are welded and the ends of the corrugations cast into a cast-iron base and rim. Both Figs. 24 and 25 show the method of bringing out leads through porcelain bushings in overhanging covers, as referred to in Art. 22.

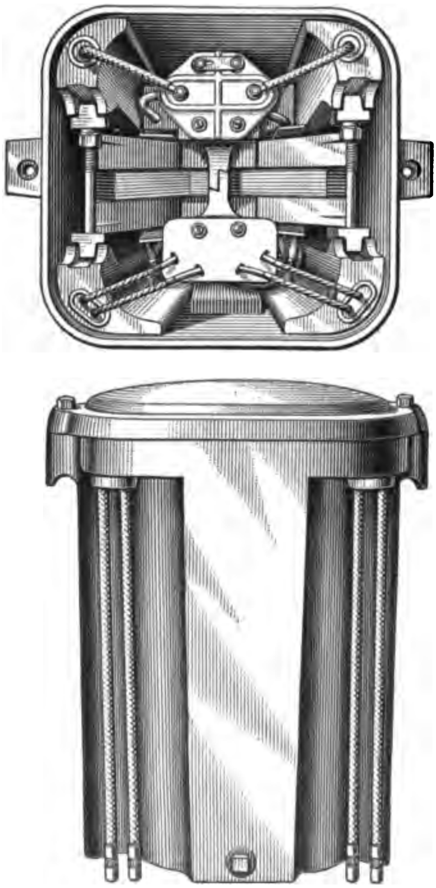


Fig. 24

31. For large outdoor transformers, the compound corrugated tank, Fig. 26, and the tubular tank, Fig. 27, are used. In the former, a very large surface is secured by providing large V-shaped corrugations that are in turn corrugated as on the medium sizes. In the tubular-tank construction, Fig. 27, a large number of pipes are welded in at the top and the bottom of the tank. The oil circulates

through these pipes and is cooled very effectively by the surrounding air. The words *oil-insulated self-cooled* are frequently applied to transformers of this type, and the construction has been employed in units as large as 3,000 kilovolt-amperes.

32. The use of oil in transformers affords the additional advantage of providing a large storage capacity for heat, so

FIG. 25

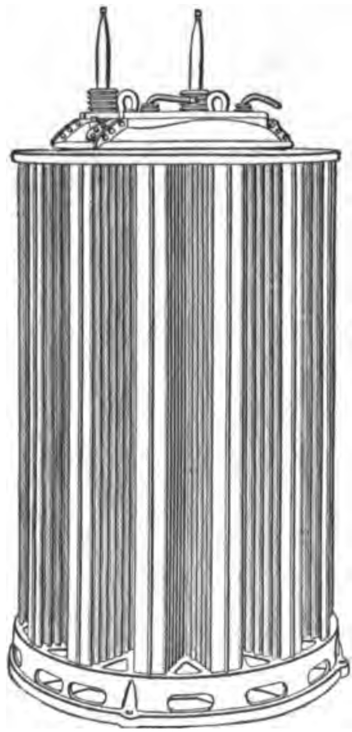


FIG. 26

that heavy overloads can be carried for short intervals without damaging the windings. The difference in temperature between copper and oil under ordinary operating conditions, is usually from 5 to 10° C., but this difference in case of overloads increases rapidly; that is, the temperature of the copper rises more rapidly than that of the oil. Therefore, ample allowance must be made if the temperature of the windings is to be judged

by that of the top oil in the transformer. The difference in temperature between copper and oil will be approximately proportional to the copper loss. For example, if at a full load the difference is 10° C., at 50 per cent. overload the copper loss will be $1.5^2=2.25$ times greater, and the difference will be $10\times2.25=22.5°$ C.; that is, the temperature of the copper is 22.5° C. higher than that of the oil. Moreover, the temperature of the oil increases in proportion to the total loss.

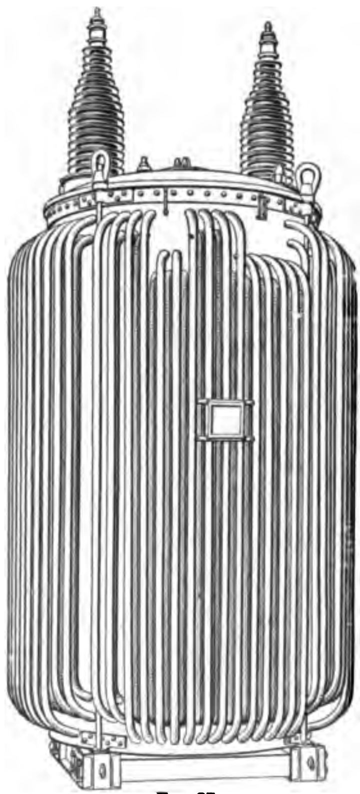


Fig. 27

33. A water-cooled transformer is one in which cold water circulates through coiled pipe in the oil surrounding the windings. This method of cooling is generally employed for transformers of 3,000 kilovolt-amperes and larger, because with these large sizes tank surface alone does not furnish enough radiating capacity. Oil and water cooling is also sometimes employed with smaller sizes, in which cases the tanks are made of cast iron. Tanks for the larger sizes are invariably made of boiler plate. The tanks are not depended on to dissipate heat; the circulating water carries it away. An external view of an oil-insulated water-cooled transformer is shown in Fig. 28, and in Fig. 29 is shown the same transformer removed from the tank, giving a good idea of the position of the cooling coils. Practically any size of transformer can be built with this construction by increasing the length of cooling coil as the size increases, in order effectually to dispose of the heat developed.

34. The temperature of the ingoing water is usually specified at 15° to 25° C., and the quantity is based on a temperature rise of the water of about 15° C., requiring about ¼ gallon per minute for each kilowatt loss. For continued overloads, the water rate should be increased, in order to limit the temperature rise. If the water supply fails, the transformer cannot be

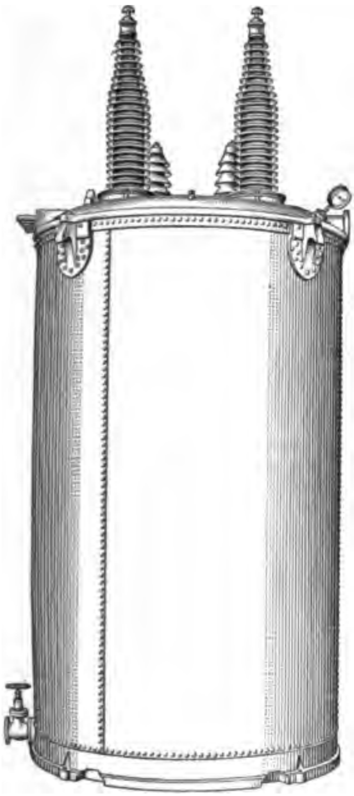


FIG. 28

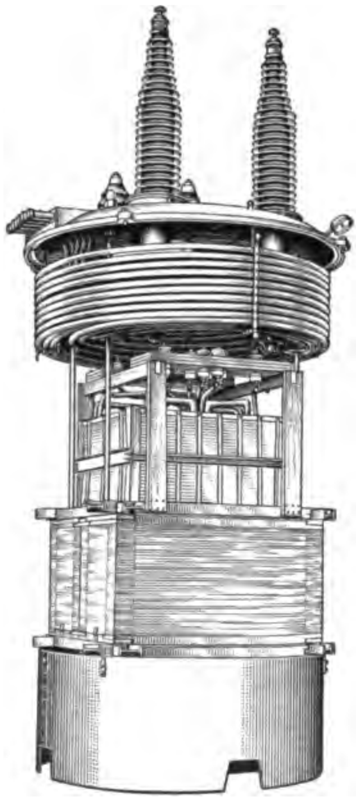


FIG. 29

operated with load except for a very short time. In such a case, even the core loss alone may be sufficient in some transformers to overheat the windings. In general, the temperature of the top oil in the center of the tank (the hottest part) should not exceed 75° C. Usually, large transformers are provided

with thermometers, and sometimes an electric bell and battery are arranged so as to sound an alarm whenever the temperature of the oil reaches, say, 65° C.

35. The cooling water often contains impurities of various kinds, for which reason an occasional inspection of the cooling coil should be made to see whether it is clogged up. The approach of this condition is usually indicated by a higher temperature rise of the oil and in aggravated cases by a restricted flow of water through the pipes. In removing the deposits, the water should first be blown out and the coils then filled with a solution of equal parts of hydrochloric acid and water. After standing an hour or so, this solution should be blown out; then, if all the scale is not removed, the operation should be repeated.

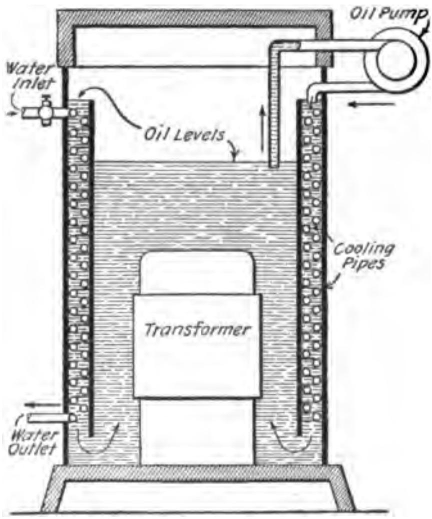


Fig. 30

The cooling coils should also be inspected occasionally for a deposit that may form on their outer surface. This deposit is especially likely to form in case of long continued overloads, and it acts as a heat insulator, thereby causing higher operating temperature. It should be carefully scraped off whenever found. If for any reason the oil is drained from the transformer, any deposit found on the windings can usually be removed by a jet of oil.

36. Forced-oil cooling means simply a means of artificially circulating oil in oil-insulated water-cooled transformers so large that natural oil circulation is too slow. The hot oil is pumped out of the top of the tank and returned to the bottom. Two methods of construction are in common use. The first requires only a pump and a motor for driving it; the second

method requires an additional cooling tank. Inlet and outlet pipes are required in both cases.

37. In the first method, which is shown diagrammatically in Fig. 30, the tank is of a double-wall construction, with the cooling pipes through which water circulates located between these walls. Hot oil is pumped from the top of the transformer to the space between the walls, so as to maintain a difference

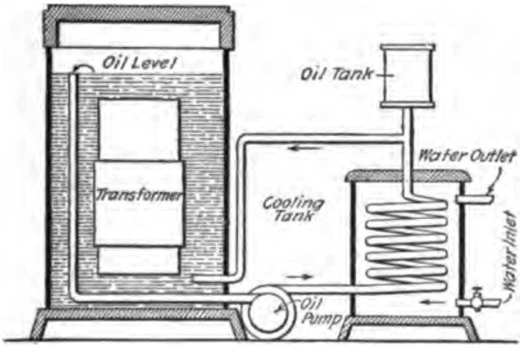


FIG. 31

in the oil levels of approximately 1 foot. This head causes downward circulation of oil over the cooling pipes, and the cooled oil is directed to the bottom of the windings, whence it rises as the heating goes on.

38. In the second method, shown diagrammatically in Fig. 31, the oil is circulated through the cooling coils located in the tank through which cold water circulates.

TRANSFORMER INSULATION

39. Transformer oil is a mineral oil obtained by partial distillation of petroleum. Such oil must not be easily ignitible; the temperature at which the ignition occurs, or the *flash point*, must be well above any temperature liable to be attained in service. Good transformer oil possesses a dielectric strength of 200 to 250 volts per mil. Samples of oil are usually tested between disks $\frac{1}{2}$ inch in diameter and spaced $\frac{2}{10}$ inch (200 mils)

apart, this being known as a *standard gap*. Good oil will break down at 40,000 to 50,000 volts on such a test.

40. Transformer oil must be absolutely free from moisture if used with even moderately high voltages. The effect of water on the dielectric strength of oil is very marked, as is indicated by the curve in Fig. 32. A sample of oil to break down at 40,000 volts on the standard gap may contain $\frac{1}{10}$ part of water in 10,000 parts of oil, by volume, yet the dielectric strength drops to less than 20,000 volts when there is 1 part of water in 10,000 parts of oil. With $2\frac{1}{2}$ parts of water for

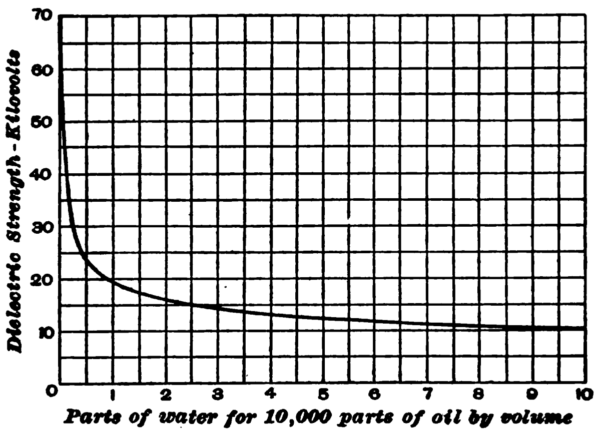


FIG. 32

10,000 parts of oil, the dielectric strength drops to 15,000 volts, etc.

Before placing a large transformer in service, a few samples of oil from it should be tested, and after installation, samples should be tested periodically. Samples should be taken from near the bottom after the oil has been undisturbed for several hours. This can be done by thrusting a long open tube to the bottom, then closing it at the top with the hand and withdrawing it. The receptacle into which the sample is placed must be perfectly clean and dry. The samples should be tested in a standard gap if possible, or if a variable voltage is not available, the gap should be adjusted for at least 200 volts

per mil. A rough practical test consists in turning the tube with oil bottom side up, when the water globules, if present, will slowly descend. If water can be detected in this manner, or if the electrical tests show a dielectric strength much less than 200 volts per mil (for transformers operating at voltages under 40,000 volts, 150 volts per mil would be satisfactory), the oil should be dried.

41. Drying Transformer Oil.—Drying transformer oil may be effected by heating it to a temperature of 100° to 120° C. Heat may be applied by immersing steam coils in the oil, placing them at the bottom of the tank, where the water settles,

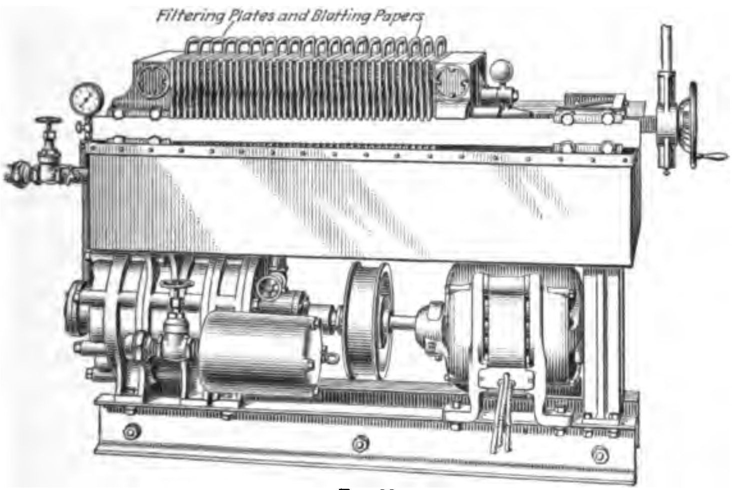


FIG. 33

or by placing a fire underneath the tank; in either case the water is vaporized and thus driven off. Another plan is to force hot air through the hot oil, the air being first thoroughly dried by passing through calcium chloride. Applying a vacuum to the tank and drawing the hot air up through all parts of the oil is also a fairly satisfactory method.

42. By far the best method of removing moisture from oil is by means of the *filter press*. This press also removes all dust and sediment, substances that materially lower the dielectric strength and that may clog the ventilating ducts.

Specially designed filter presses are built for this work, one of them being shown in Fig. 33. In this press, the oil is forced through several layers of a specially prepared blotting paper that are held between cast plates provided with a large number of filtering surfaces. Owing to the greater capillary attraction between paper and water than between paper and oil, the moisture is retained by the paper and the oil allowed to pass through. All the sediment is of course caught by the first layer. If the papers are removed frequently, every trace of moisture can be eliminated from the oil. For the best operation, the temperature of the oil should be between 25° and 75° C. By connecting the filter inlet to the bottom of the transformer tank and discharging back into the top of the tank, the filter press can be used for drying the oil of a transformer in operation.

43. Because water has such an injurious effect on the insulating qualities of transformer oil and other insulating materials, great care must be taken to keep moisture out of a transformer, especially one that is for high-voltage service. Such a transformer should not be allowed to stand out in the weather for a long time without excitation, even if it is designed for outdoor service. If the temperature of the interior of the transformer is kept a few degrees above that of the surrounding air, the effects of moisture will to a great extent be eliminated.

44. To prevent the admission of moisture to the windings during shipment, the practice of shipping transformers filled with oil is quite common where the excessive size and weight of the assembled unit is not prohibitive. To make sure, however, that the transformer is free from moisture before being put in service, the oil should be tested, even if it has been shipped in the transformer.

Where the windings are shipped out of oil, and the transformer voltage is greater than, say, 20,000, the windings should be carefully dried out before installation; this statement applies to large low-voltage units also.

Transformers using oil are in most cases provided with a gauge for determining the height of oil, the gauge being marked to show the proper oil level. The maintenance of this level

is very important for the proper operation of the transformer, particularly with the large self-cooled, tubular-tank construction previously mentioned; if the upper ends of the cooling pipes are uncovered, their function is entirely lost and the transformer will overheat.

45. Drying Transformer Windings.—Drying transformer windings can be accomplished in either of two ways. The first consists in forcing sufficient current through the windings to raise their temperature to approximately 80° C. This is done by short-circuiting one winding and applying sufficient voltage to the other to give the required current, ordinarily about one-fourth full-load current. The voltage required will approximate, say, 1 per cent. of the normal voltage for that winding. The temperature should be determined by the increased resistance of the windings, 1 per cent. increase corresponding to a temperature rise of approximately 2.4° C. In no case should the temperature exceed 80° C., corresponding to an increased resistance of approximately 33 per cent. If impossible to use the resistance method, use may be made of spirit thermometers placed in direct contact with the low-voltage coils. The transformer should preferably be out of its tank during this run, or the tank should be opened by removing all possible covers. Current should be maintained for at least 24 hours, and for very large transformers or high-voltage units, this time should be increased to 60 or 70 hours.

The second, and better, method consists in forcing heated air up through the windings, with the transformer in its tank. The temperature of the air should be approximately 80° C., and the process should be continued for at least 2 or 3 days, or longer if the windings are unduly moist. Heating outfits, each consisting of a blower and an electrical heater, are on the market for this purpose. Such outfits find a wide field for usefulness among large users of high-voltage transformers.

APPLICATION OF TRANSFORMERS

46. Transformers are also classified according to their application, the principal classes being *power transformers*, *lighting transformers*, *measuring instrument transformers*, *series transformers* for series street lighting, *constant-current transformers*, *testing transformers*, and *miscellaneous applications*. Each of these classes has some peculiar features of design and construction.

47. Power transformers, for stepping up or stepping down the voltage at the ends of transmission lines, are usually of fairly large size and are insulated for high voltage. Ruggedness of construction is of paramount importance in such transformers, for they are often subjected to heavy overloads and to abnormal increases in voltage due to lightning discharges, as well as to high-frequency stresses caused by switching the line on and off and by other disturbances. When installed outdoors, particular care is necessary to make the casings moisture-proof, and gaskets are accordingly used under all covers. For outdoor service the leads are generally special, usually having porcelain insulators. For high-voltage work leads of the oil-filled type or the condenser type are used.

48. Lighting transformers are in a majority of cases for outdoor service, being usually mounted on poles. They are invariably oil-cooled and usually of distributed-core construction. Both high- and low-voltage coils for such transformers are generally wound in two parts, and these may be connected either in series or in parallel, depending on the voltage requirements. Lighting transformers for use in manholes in connection with underground distributing systems should be of more rugged construction than those for mounting on poles. The casings of both manhole and pole-type transformers must be water-tight, and the connections should be so arranged that the transformer may be connected or disconnected from the line without the necessity of opening the tank. An oil gauge is usually provided for determining the proper oil level.

49. Measuring-instrument transformers to reduce high voltage for safe use at switchboards and to reduce high alternating currents so as to avoid excessively heavy leads to switchboards are small *potential transformers* and *current transformers*. Instruments for use with such transformers have scales calibrated to read the line voltage or the line current to be measured.

Fig. 34

A **potential transformer** of this type is usually oil insulated and is connected across the line. As the ratio of primary to secondary voltage should remain very nearly constant, such transformers must have low resistance and reactance. Fuses should always be connected on the high-voltage side of a potential transformer, and the low-voltage winding should be grounded in order to protect operators.

In a **current transformer** for use with an ammeter, the primary winding is connected in series with the line, and the secondary in series with the ammeter. The voltage in the secondary circuit varies with the line current, and, the resistance of the circuit being constant, the current in the ammeter varies with that in the line. The iron loss in the transformer must be low in order that the magnetizing current may not appreciably affect the ratio of current transformation. Fig. 34 shows a common form of current transformer with the case opened.

The primary current in a current transformer is the line current, which is unaffected by the secondary current. The secondary current, however, opposes the magnetizing effect of the primary current, so that the resultant flux in the transformer is low, causing low induced secondary voltage. If the secondary circuit is opened, the flux becomes high, causing high induced voltage and usually a breakdown of the insulation. The secondary winding of a current transformer should, therefore, be short-circuited before disconnecting the instrument.

50. Series transformers are also used in connection with street lighting where incandescent lamps are in series, a small transformer being used with each lamp. The primary is connected in series with the line and the secondary across the lamp.

Means for automatically short-circuiting the secondary winding in case of a lamp burn-out are usually provided in the form of a thin insulating film between two spring contacts in parallel with the lamp. When the circuit opens and the voltage across the secondary rises, it punctures the film, thereby short-circuiting the secondary.

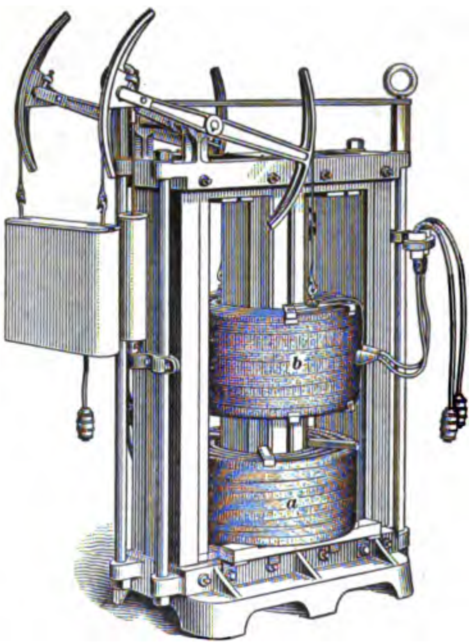


FIG. 35

51. Constant-current transformers are used in series arc-lighting circuits in which the current must remain constant while the number of lamps in series varies. Fig. 35 shows the appearance of such a transformer removed from its oil tank. The stationary primary coil *a* is connected to a source of alternating electromotive force, and the movable secondary coil *b* is connected to the lamp circuit. In order to maintain constant secondary current, the voltage of the secondary must vary with the number of lamps. The constant secondary current in different circuits is usually some value between 4 and 7.5 amperes, depending on the character of the lamp. On increasing the resistance of the secondary circuit by switching on additional lamps, the current automatically adjusts itself by changing the relative position of the secondary and primary coils.

The secondary coil is suspended, as shown, from a counterbalanced rocker-arm. The tendency of the coil to move toward the primary is opposed by both the counterweight and the magnetic repulsion between the coils caused by the current. At full load, the coils are only an inch or two apart. If the resistance of the secondary circuit is decreased, the momentary increase in current results in a greater repulsion of the coils and they move farther apart. The separation of the coils in turn results in an increased leakage flux, thus reducing the useful flux through the secondary, and the voltage decreases to correspond to the reduction in load.

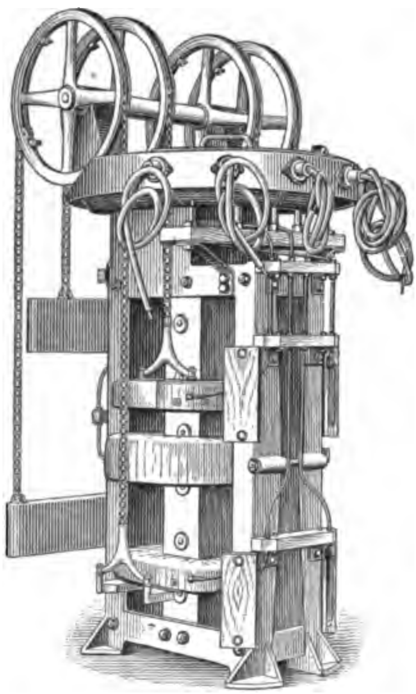


Fig. 36

52. Larger constant-current transformers than shown in Fig. 35 are provided with two secondary coils, one above and one below the stationary primary, as shown in Fig. 36. The secondary coils are counterbalanced and move toward or from the primary as the resistance of the secondary circuit becomes greater or less. A separate circuit of from 50 to 75 arc lamps each can be operated from each secondary coil, and the current in each circuit can be adjusted to remain constant at a value independent of the current in the other circuit. This value is adjusted by changing the counterbalance weights.

When switching on a circuit of lamps, the moving element should be set for minimum voltage (maximum leakage) in order to prevent excessive initial rush of current. In some

cases, a latch is provided automatically to hold the secondary coil in position for maximum leakage until the lamps have started.

53. Testing transformers are used in making dielectric strength tests of materials, such as oils and other insulators. The low-voltage coils of such transformers are made to suit the voltages of ordinary lighting or power circuits, and the high voltage coils may range from 10,000 volts up to possibly several hundred thousand volts.

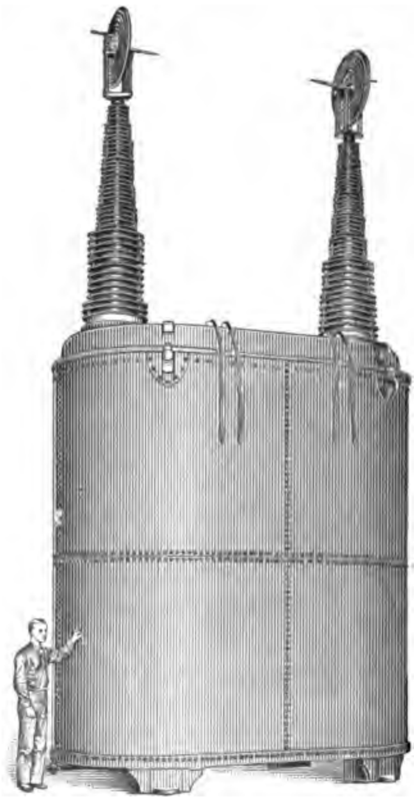


FIG. 37

Testing transformers are of the oil-cooled type, and special attention is given to their insulation. Fig. 37 shows a testing transformer for a maximum secondary voltage of 750,000 and, therefore, capable of producing a spark between needle points set over 6 feet apart. Extra-large, oil-filled leads are required to bring out the terminals of the high-voltage winding, and these are surmounted with choke coils for protecting the end turns of the transformer from high-frequency oscillations. The interior view, Fig. 38, shows the core-type construction and the extra-heavy insulation. A very large number of high-voltage coils are connected in series, the diameters decreasing toward the top of the legs as the voltage difference between legs increases. The low-voltage coils are placed next to the

core, separate leads being brought out from each of the two coils, so as to enable their connection in series or in parallel.

54. Among **miscellaneous applications** are *transformers* for *electric furnaces* and for *welding*, in which the secondary is bar wound, sometimes with only one turn, and capable of carrying several thousand amperes; also the *pipe*

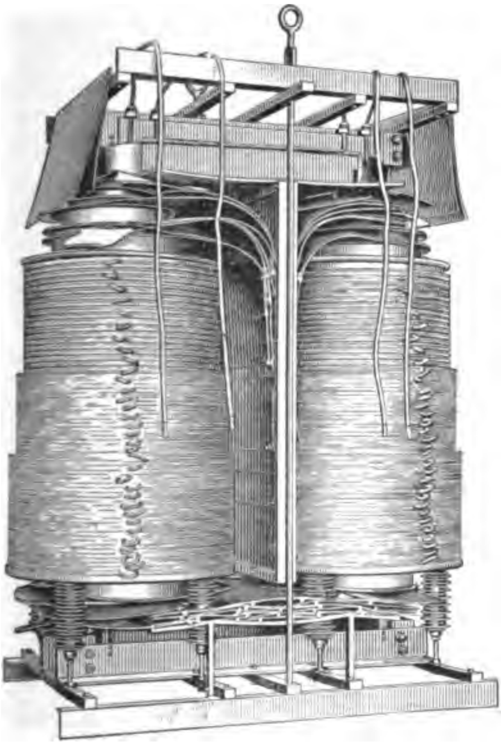


Fig. 38

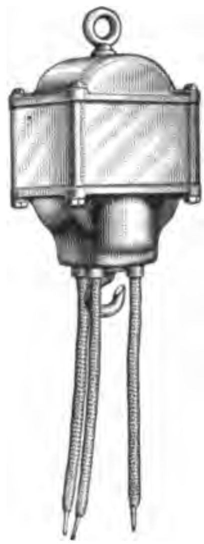


Fig. 39

thawing transformer with variable external resistance for regulating the voltage; and the telephone insulating transformer to prevent injury to the operator by high voltages induced by proximity to power transmission lines.

55. A large class of transformers and autotransformers is used for reducing line voltage to some particular value best

adapted to the load device, such as *sign-lighting transformers*, where 110 volts is stepped down to, say, 25 volts for low-voltage tungsten sign lamps; or *arc-lamp autotransformers*, where 220 volts is stepped down to the voltage required for best operation of the arc. A small shell-type unit of this latter class is shown in Fig. 39. Another class of transformers and autotransformers is used for small work, such as ringing bells, running electrical toys, and lighting individual low-voltage lamps.

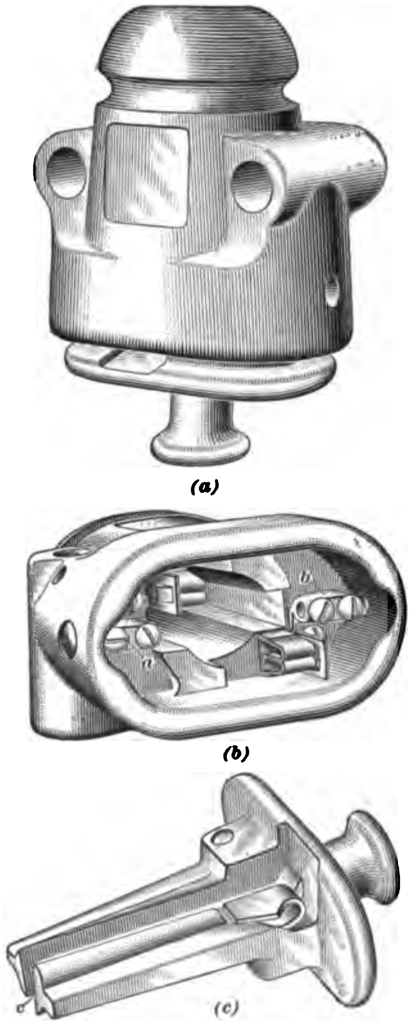


FIG. 40

56. Fuse Protection. Fuses, or cut-outs, are usually connected in series with the high-voltage winding of a lighting transformer, in order to protect the winding during short-circuits or other abnormal current conditions. Fig. 40 (*a*) shows a *transformer cut-out* that serves also as a disconnecting switch. The line and one end of the winding are connected to terminals *a* and *b*, as shown in (*b*). The removable part, which is shown in (*c*), is provided with two blades fitting snugly into the terminals. The blades are insulated from each other, except as connected by a fuse wire that lies in a furrow *c* running around the end of the movable

part. The fuse is proportioned to melt and thus open the circuit at a predetermined current near the maximum that can be carried safely by the transformer windings.

CHARACTERISTICS OF TRANSFORMER

57. Regulation.—If a constant voltage is impressed on the transformer primary, the resistance and reactance drops cause the secondary terminal voltage to vary with variations in load. At no load, the voltages will correspond to the ratio of turns; as load is increased, the secondary voltage will become less; and as load is decreased, the secondary voltage will become greater. In transformers that are supplying lighting circuits, this is particularly undesirable on account of the resulting unsteadiness in lights. A transformer in which the variation of secondary voltage is small from no load to full load when the impressed voltage is constant is said to possess *good regulation*.

58. In practice, the regulation is usually specified as the percentage increase in the secondary voltage of the transformer as the load is reduced from its normal value to zero. To determine the regulation of a transformer, a constant alternating voltage of the normal value should be applied to the primary, and the terminal voltage of the secondary should be noted both at no load E_s and at normal load E_{so}; then

$$\textit{percentage of regulation} = \frac{E_s - E_{so}}{E_{so}} \times 100$$

In specifying the regulation of the transformer, it is necessary to mention the power factor at which this regulation is expected. For example, the regulation of a transformer may be satisfactory at unity power factor, but entirely unsatisfactory at a power factor of, say, .75 per cent.

59. Transformer Losses.—The energy delivered by a transformer is always less than the energy received from the mains, on account of the losses that take place within the transformer. These losses are:

1. The $I^2 R$ *loss*, or *copper loss*, due to the resistances of the primary and secondary windings, which, in commercial transformers at full load, is usually from 1 to 2 per cent. of the power delivered.

2. The *core loss*, due to the alternating flux in the core; this loss is composed of two parts, *hysteresis loss* and *eddy-current loss*. Hysteresis loss is due to magnetizing the core first in one direction and then in the other; it is directly proportional to the frequency and depends on the maximum flux density and on the quality of iron used. *Eddy-current loss* results from the circulation of the currents induced in the core by the variation of the flux. To reduce the eddy currents, the resistance of their path in the core is made high by laminating the iron in the direction at right angles to that in which the currents tend to flow. All transformer cores are therefore made of thin sheet iron punchings, which are insulated from each other by thin sheets of paper, by coating them with some insulating substance, or by the scale that is usually produced on the sheets during the process of annealing. In this manner, the eddy-current loss is reduced to about 20 per cent. of the total core loss in the transformer. Eddy currents are proportional to the square of the frequency, the square of the maximum flux density, and the square of the thickness of the laminations.

60. A great amount of developmental work has been done on transformer iron for the purpose of reducing the losses. One difficulty, which has now been overcome, was due to the fact that the core loss of a transformer in service gradually increases. This characteristic, commonly known as *aging*, has been eliminated by carefully annealing the iron. It has been found also that if transformer iron is made to contain almost 3 per cent. of silicon, the core loss is considerably reduced. This has given rise to *silicon steel*, which is now extensively used in transformers and particularly in lighting transformers. The core loss in silicon steel is about 75 per cent. of the loss in ordinary iron, when operating at the same flux density.

61. Determining Transformer Losses.—To determine core loss of a transformer, connect it to a source of low-voltage

supply, as shown in Fig. 41. The high-voltage winding is to be left open and the low-voltage coils are to be connected as for usual operation; that is, either in series or in parallel. In Fig. 41 the low-voltage coils are shown connected in parallel.

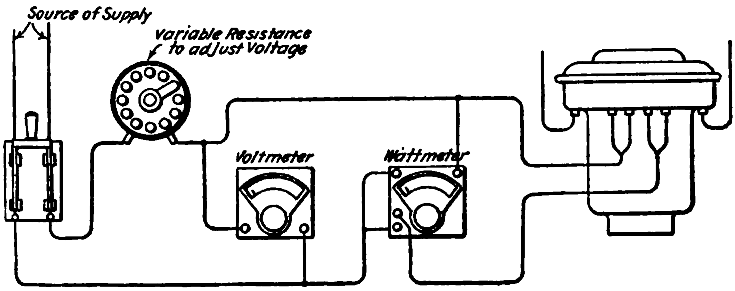


FIG. 41

The normal low voltage at the proper frequency is then applied to the low-voltage coils, and the wattmeter reading is the core loss.

62. To determine the copper loss, connect the transformer as shown in Fig. 42. The low-voltage windings are to be short-circuited, and the voltage should be so adjusted across

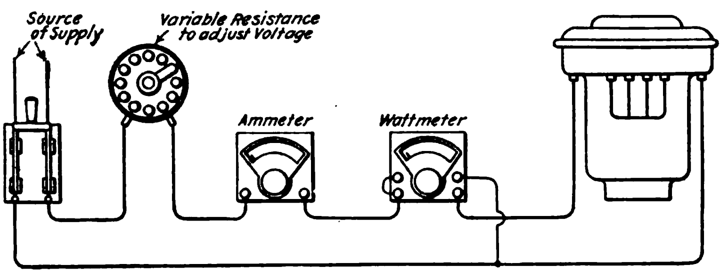


FIG. 42

the high-voltage coils that the full-load current is indicated by the ammeter. The wattmeter reading then indicates the full-load copper loss.

The total losses of the transformer are the core loss and the copper loss.

63. Efficiency.—The efficiency of a transformer may be calculated as follows:

$$per\ cent.\ efficiency = 100 \times \frac{energy\ output}{energy\ input};$$

or, if the losses are known,

$$per\ cent.\ efficiency = 100 \times \frac{energy\ output}{energy\ output + core\ loss + copper\ loss}$$

The core loss is constant, taking place during the total time that the transformer is excited; on the other hand, the copper loss depends on the load, being small at light loads and increasing with the square of the load current. The relative amounts of the two losses depends on the class of service for which the machine is designed. If the transformer is connected continually to the exciting mains, but is loaded only part of the time, the core loss becomes a much more important consideration than the copper loss.

64. Efficiency Tests.—The characteristics of small transformers can be determined by a load test, the connections being as shown in Fig. 43, in which ammeters are indicated at *a*, voltmeters at *v*, and wattmeters at *w*. Rated voltage is applied to the primary, and the secondary load is adjusted to any desired value up to full capacity. The wattmeter on the primary side then indicates input and that on the secondary side, output; the difference between input and output is the loss, and the ratio $\frac{output}{input}$ is the efficiency. The loss and the efficiency at any load can be obtained in this way.

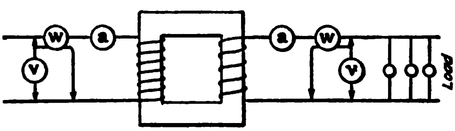


FIG. 43

65. When it is inconvenient to load a transformer, the losses are determined separately, and from these the efficiency is calculated. Where two transformers of similar rating are available, they may be tested under actual load conditions by the so-called *loading back*, or opposition, method. The two transformers are connected as if for operation in parallel,

as described later, and the external connections are made as shown in Fig. 44, in which the reference letters have the same significance as those in Fig. 43. The low-voltage coils, Fig. 44, are connected in parallel and are subjected to their rated voltage; the high-voltage coils are connected in series and subjected to voltage high enough to establish full-load current in them. The wattmeter on the low-voltage side then indicates the iron loss, in watts, and the wattmeter on the high-voltage side indicates copper loss, both these losses in this case being at full load. Proper frequency must be employed in both cases.

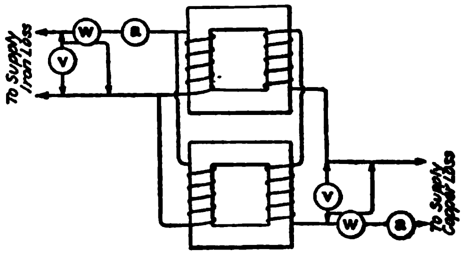


FIG. 44

INTERCONNECTION OF TRANSFORMER COILS

66. Interconnection of Secondary Coils.—Each lighting transformer is usually provided with a low-voltage winding in two parts, in order to facilitate connection for two voltages; one voltage is obtained by connecting the coils in series and the other by connecting them in parallel. It is customary to bring out secondary leads in such order that they can be connected as in Fig. 45 for parallel operation and, as in Fig. 46, for series operation. Fig. 47 shows the coils and their connections, the lettering corresponding to that on Figs. 45 and 46. The arrows indicate an instantaneous voltage condition.

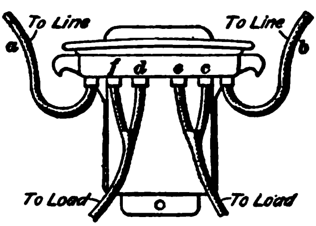


FIG. 45

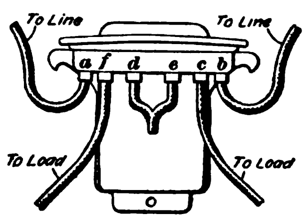


FIG. 46

The secondary voltage is always 180 time-degrees behind the primary voltage. If the primary and secondary coils are wound in the same direction and the leads are symmetrically brought out, the voltage from *c* to *d* and from *e* to *f*, Fig. 47, is thus always opposite in direction to the voltage from *a* to *b*. Therefore, to connect the two secondary coils in series, leads *d* and *e* must be joined, while to connect the coils in parallel, lead *c* must be joined to *e*, and lead *d* to lead *f*.

67. The primary and secondary leads are often brought out on opposite sides of the transformer instead of as shown in Figs. 45 and 46, and the secondary leads are not always brought out in the order indicated in Fig. 47. For this reason, the connections should always be checked as follows: Connect the primary winding to the line; next determine which leads belong to the same secondary coil by connecting one lead to an incandescent lamp and touching the other terminal of the lamp to each of the remaining three leads, one after the other, until the lighting of the lamp indicates that the other terminal of the coil is touched. The primary leads can be identified by their size, being smaller than the secondary leads.

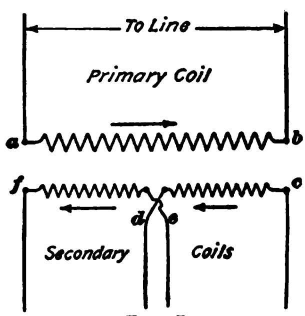


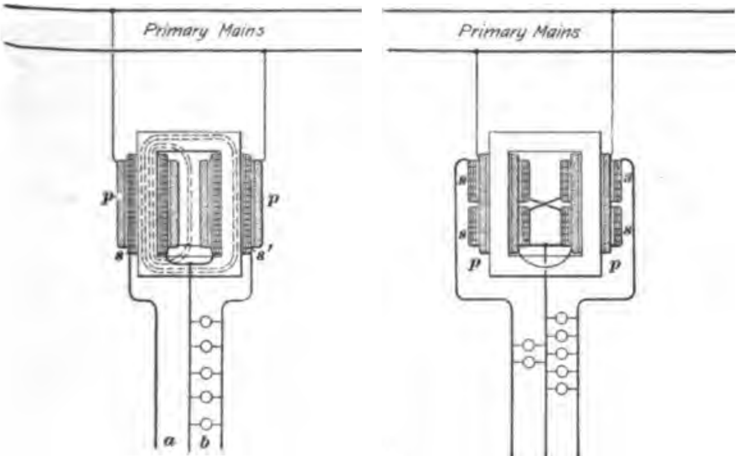
FIG. 47

68. To connect the coils in series, temporarily join two leads, one from each coil, and connect the lamp, or possibly several lamps in series, between the two remaining terminals. If the lamps burn brightly, when the primary is excited, the coils are in series, their voltages being added. If the lamps remain dark, the two voltages oppose each other, showing that the connection is wrong for series connection. The rated voltage of the test lamp, or the series of test lamps, must equal or exceed the voltage to be tested or the lamp may burn out.

69. To connect the coils in parallel, temporarily join two leads, one from each coil, and connect the lamp between the

two remaining leads. If the lamp remains dark with this connection, while the primary is excited, the leads giving no light may be safely joined together and the temporary junction may be made permanent. If the lamp lights, the leads are improperly selected for parallel connection. These tests are important, for if the wrong leads are joined the transformer may be burned out.

70. Transformers on Three-Wire System.—When core-type transformers are used on a three-wire system, as shown in Fig. 48, the voltage on the two sides of the circuit



(a) FIG. 48 (b)

may become greatly unbalanced if the load is not equally divided. For example, in the extreme case, view (*a*), where the side *a* has no load, the secondary coil *s* will have no current and will therefore set up no counter magnetization, whereas coil *s'* will have a current due to the load on side *b*. Thus, the magnetic flux in the two sides of the core becomes unequal, as is roughly indicated by the dotted lines, and the secondary electromotive force is considerably higher on the side *a* than on the side *b*. In order to overcome this difficulty, the secondary may be wound in a number of sections *s*, view (*b*), and these coils cross-connected as indicated. The result is

that no matter how unbalanced the load may be, the demagnetizing effect of the secondary is the same on both cores and the voltage remains practically the same on both sides.

71. Operation in Parallel.—Transformers are often connected in parallel and the method of connecting is precisely the same as in connecting the two coils of the same transformer. Connect the primaries of both transformers to the line and interconnect the coils of each transformer separately in parallel or series, as the case may be; then treat the interconnected secondaries as single coils. Two transformers connected in parallel are shown in Fig. 49.

The two transformers to be operated in parallel must have the same ratio of transformation; otherwise, the secondary voltages will be unequal and the difference between the voltages will cause a current in the local circuit that joins the two transformers. This current induces a current in the primaries, and as the only opposition to it is the impedance of the two transformers, even a small voltage may cause a heavy local, or short-circuit, current.

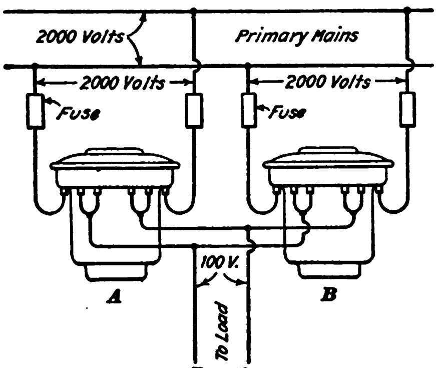


FIG. 49

72. Sharing the Load.—Transformers connected in parallel should share the total load on all of them, in proportion to their ampere capacities. If they do not, the cause may be wrong connections or differences in voltage ratios; but the most common cause of unequal load division is difference of impedance. It is assumed that when two transformers with equal voltage ratios are operating in parallel, the current in each will be such that their impedance drops are equal.

73. The division of total current between two transformers connected in parallel may be predetermined graphically as

follows: From the values of resistance and reactance, the impedance triangles of the two transformers are drawn relatively to each other, as shown in Fig. 50. The impedance triangle of the transformer A, Fig. 49, is represented by the triangle $a\,b\,c$, and that of the transformer B, by the triangle $c\,d\,e$. When two circuits are connected in parallel, the current divides in inverse proportion to the impedances. Thus, ac and ce, representing impedances Z_A and Z_B, respectively, represent the relative values of the currents also; but $a\,c$ represents the current I_B in the transformer B, and $c\,e$ represents the current I_A in the transformer A; therefore, their resultant $a\,e$ represents the total current in both.

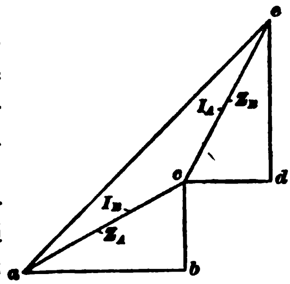


FIG. 50

74. Phase Transformation.—Devices intended for operation on two-phase systems may be operated from three-phase circuits by means of transformers connected according to Scott's system of connections. By the same means, devices intended for three-phase circuits may be operated from a two-phase system. By the Scott system, two especially designed transformers are connected as shown in Fig. 51. The

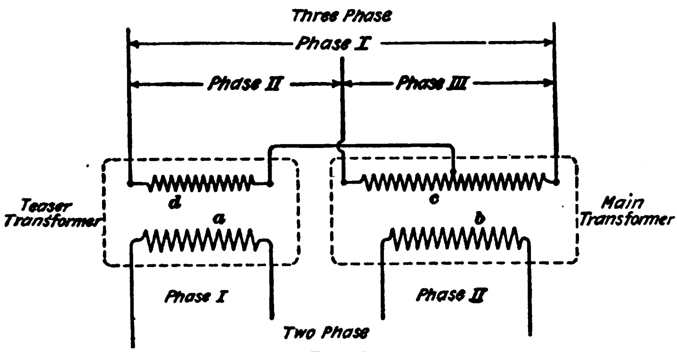


FIG. 51

two similar windings a and b are connected to a two-phase system, or device, and the interconnected windings c and d

are connected to a three-phase device or system. The winding c is called the *main winding* and the winding d, connected to the middle point of the winding c, the *teaser winding*. The number of turns in the teaser winding is only 86.6 per cent. of the turns in the main winding. The voltage and current relations of the Scott connection are explained in *Alternating Currents*, Part 2.

75. Polyphase Connections.—In three-phase systems, the separate phases of a three-phase transformer or of three single-phase transformers can be grouped into one of the four combinations:

1. High voltage Δ; low voltage Δ.
2. High voltage **Y**; low voltage **Y**.
3. High voltage Δ; low voltage **Y**.
4. High voltage **Y**; low voltage Δ.

The fact should be noted that in any of these combinations at non-inductive load the voltage and the current of each phase are in phase.

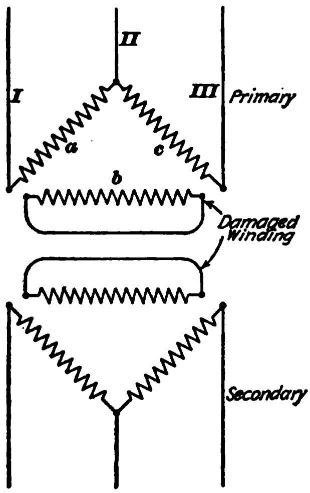


FIG. 52

76. Transformers connected *delta-delta* possess the advantage that in case the winding of one phase is rendered inoperative, service can be maintained on the remaining two windings. The damaged winding should be completely disconnected from the circuit in any case. In a three-phase core-type transformer, both the primary and secondary coils of the damaged winding should be left open; and in a shell-type transformer both these coils should be short-circuited upon themselves, as shown in Fig. 52.

The connection of two sets of transformer windings on a three-phase circuit, as in Fig. 52, is called *open-delta*, or **V**, *connection*, and is sometimes used as a regular three-phase connection. The voltages impressed across the two windings are the same as in the delta-delta connections. The currents in the windings, however, are changed, because the current in

line *I* or *III* has only one path, *a* or *c*, instead of the two paths, *a* and *b* or *c* and *b*, with the delta-delta connection. The current in the windings is therefore equal to the line current.

77. The **T**-*connection*, shown in Fig. 53, is sometimes employed for operating two single-phase transformers on a three-phase circuit. In order to use this connection, one transformer must be provided with leads from the middle point of each of its windings, and the other from a point on each winding that will give only 86.6 per cent. of full voltage. Because of these special features, the **T**-connection is not used so much as the **V** connection.

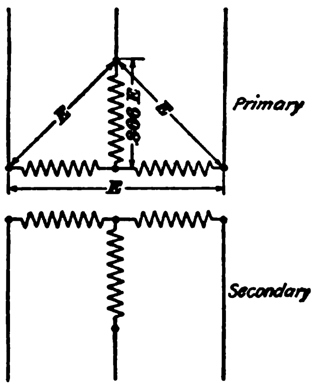


FIG. 53

78. For operating large rotary converters, six-phase voltages are very often employed. Such converters have six collector rings, across which are voltages as given in the diagram, Fig. 54. These voltages may be obtained from three-phase voltages by employing transformers having two sets of secondary windings. The primary side may be connected either **Y** or delta, and the secondary side may be in accordance with either Fig. 54 (delta-delta) or Fig. 55 (**Y Y**). The triangle *1–3–5*, Fig. 54, represents one delta, and the triangle *2–4–6*, the other. Parallel lines as *1–5* and *2–4*, are secondary windings in the same phase. In Fig. 55, *1–3–5* repre-

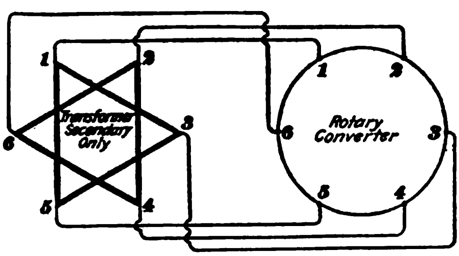


FIG. 54

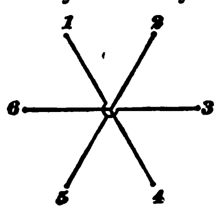


FIG. 55

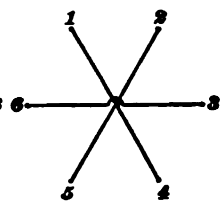


FIG. 56

sents one Y and *2–4–6*, the other. Six-phase voltages may also be obtained from a single set of secondary windings by connecting each phase to diametral points in the rotary converter, as in Fig. 56. This is called *diametral connection; 1–4* is one winding, the ends of which can be connected to the collector rings *1* and *4* of the rotary converter shown in Fig. 54.

ALTERNATING-CURRENT RECTIFIERS

VOLTAIC ARC AND STORAGE BATTERY

1. An **electric,** or **voltaic, arc** is a bow of intensely hot flame caused by the passage of electricity through space intervening between two electrodes. This flame may or may not be luminous, depending on whether anything that is luminous when heated is present in the arc; in some cases, one or both electrodes are heated until luminous. Opening any electric circuit in which electricity is flowing causes an arc; if this arc is very small, it is usually called a *spark*. To carry electricity across open space between electrodes requires voltage proportional to the length of the space, or arc.

2. A **storage battery** is a device for storing electricity. It is sometimes called an *accumulator* and, more rarely, a *secondary battery*. Properly, a battery consists of several cells, each cell containing two or more plates of metal or metallic compounds immersed in a chemical mixture in a liquid state, called an *electrolyte*. The plates are suspended in the electrolyte so that they have no direct metallic contact with each other except through an external circuit; they are equipped with terminals for the connection of electric conductors.

In passing through the cell, direct current traverses the electrolyte between the plates and causes chemical changes. The process of passing current through storage batteries by means of an external voltage is known as *charging* them. The plate by which the current enters the cell while charging is known as the *positive plate*, and that by which it leaves, the

negative plate. As the process of charging continues, the voltage across the battery terminals increases until it reaches a value beyond which little increase can be obtained; the battery is then said to be *charged*. During the process, chemical changes have occurred in the plate surfaces and in the electrolyte. These changes leave the materials in an unstable condition, such that if the positive and negative plates are connected electrically through an external circuit, the changes will recur, causing electricity to flow through the external circuit and through the cell in a direction the reverse of that followed while charging. This process is known as *discharging* the cell.

RECTIFYING DEVICES

CLASSIFICATION

3. Alternating current, on account of being so economically transmitted, is more commonly employed than direct current for lighting and for industrial motor operation. As direct current is essential for some purposes where the general current supply is alternating, means of changing from one kind of current to the other, that is, means of *rectifying* the alternating current, are in demand.

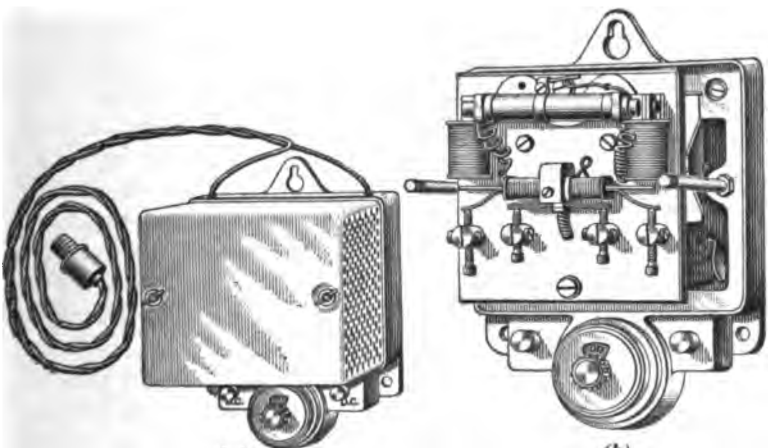
The various devices employed for this purpose may be classified as follows: *Mechanical* and *electromagnetic* combined, as motor-generators; *electromagnetic* alone, as rotary converters; *synchronous switching*, as synchronous commutating switches and mechanical, or vibrating, rectifiers; and *valvate*, as electrolytic rectifiers and rectifiers in which vapor arcs are used, a specific example being the mercury-vapor arc. Valvate devices depend for their operation on the peculiar characteristics of certain materials that act as valves, permitting current to pass in only one direction.

MECHANICAL AND ELECTROMAGNETIC RECTIFIERS

4. Motor-generators and **rotary converters** may be classed as mechanical and electromagnetic rectifiers. Both are general in application, being most used where comparatively large quantities of energy are to be converted. The motor generator, consisting of an alternating-current motor coupled, belted, or geared to a direct-current generator, receives and delivers energy at any desired voltage ratio; in a rotary converter, or synchronous converter, as it is frequently called, the ratio of direct-current voltage to alternating-current voltage is fixed. Motor-generators and rotary converters are described later.

SYNCHRONOUS SWITCHING RECTIFIERS

5. Synchronous commutating switches, or commutators running in synchronism with the alternating-current supply



(a) (b)

FIG. 1

system and operating in a manner similar to the commutator of a direct-current generator, are not a commercial success.

6. Mechanical, or vibrating, rectifiers are in successful use in small capacities for charging batteries of three or four cells each, such as are used for lighting and ignition in automobiles. These rectifiers consist essentially of switches that open and close automatically in synchronism with the alternating current that is being rectified. They operate in such a way as to intercept or rectify current half waves in one direction only.

7. Fig. 1 illustrates one type of mechanical, or vibrating, rectifier, view (*a*) showing it complete, and view (*b*), with its cover removed. Fig. 2 illustrates its connections and the principle of operation. The secondary of a small transformer is connected to two stationary platinum-tipped contacts *a* and *a'* through regulating resistances *b* and *c*. Upper contacts *a* and *a'*, are carried by a pivoted direct-current magnet that serves as the armature of two alternating-current magnets; these magnets are connected in series with adjustable resistance *d* across one-half of the transformer secondary. The alternating-current magnets are so connected that, although their magnetic polarity changes with each current reversal, the same polarities are presented to the pivoted armature at every instant; that is, both are alternately positive and negative together as the current reverses. The armature is polarized by a direct-current winding connected with the battery being charged, one end being always positive and the other negative. Each end is therefore alter-

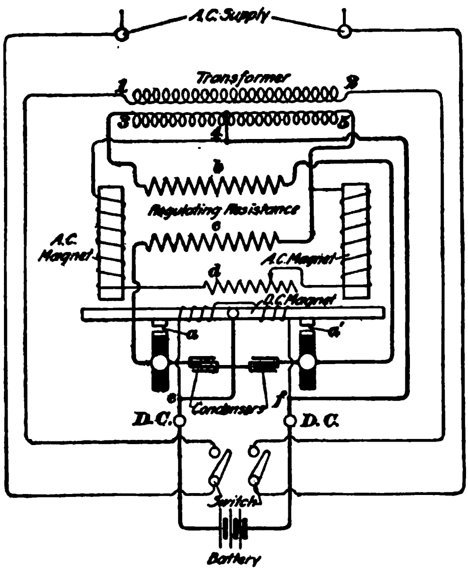


FIG. 2

nately attracted and repelled by the poles of the alternating-current magnet above, thus keeping the armature vibrating in

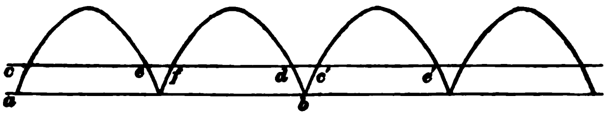


FIG. 3

synchronism with the alternating current and making contact first on one side and then on the other.

8. These contacts close at proper instants to rectify each negative half wave, giving a pulsating direct voltage and current, as represented in Fig. 3. In order to operate with minimum sparking, the contacts are adjusted to make and break at instants when the current is zero. In Fig. 3 the line *a b* represents zero voltage, and the line *c d*, battery voltage. Only the rectified voltage above the battery voltage, or the part repre-

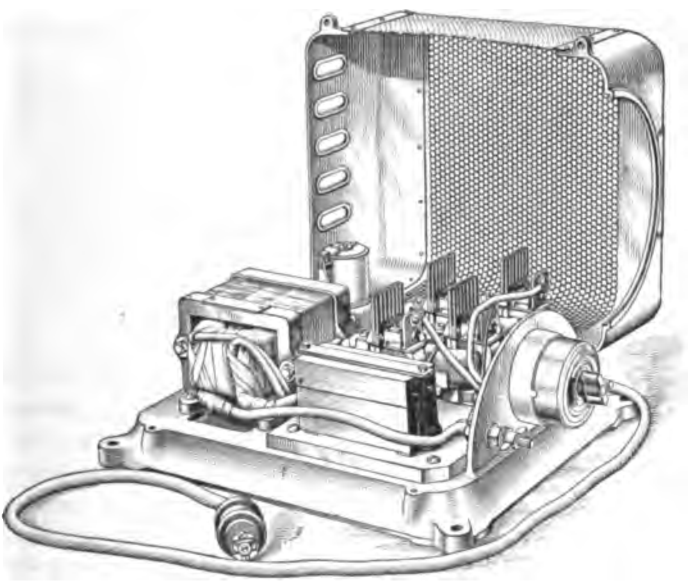


FIG. 4

sented by the curves above the line *c d*, is effective in charging. The contacts are therefore timed to close at instants

corresponding to points *c* and *f* and to open at instants corresponding to points *e* and *d*. If either pair of contacts were closed at points below the battery voltage, the battery would discharge through the rectifier. The period represented by the space *e f* lapses between the instant contact is broken on one side and made on the other by the vibrating armature.

By this means, both alternating-current impulses, or both half waves, are utilized. One passes from point *3*, Fig. 2, through the path *b–a'*–armature and pivot–*e*, where the current divides, part passing through the battery and part through the direct-current magnet to the point *f*, where the two parts unite and pass to point *4* of the transformer. The other impulse, starting from point *5*, passes through the path *c–a*–armature and pivot–*e*, from which the return to point *4* is the same as before. The current from point *e* is thus continuously in one direction through the battery and the direct-current magnet.

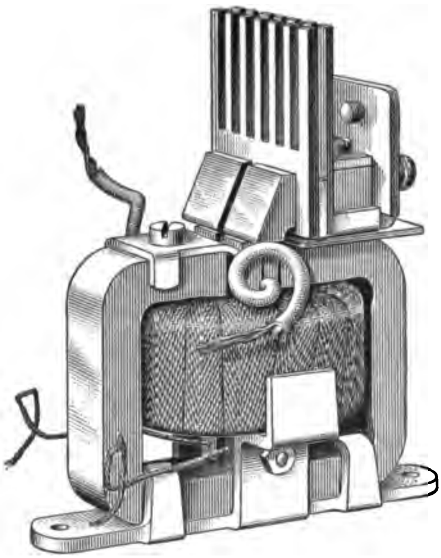


FIG. 5

If the contacts *a* and *a'* are closed and opened at the exact instants of zero current, no sparking occurs. The resistor *d* serves to adjust the operation of the contacts and the condensers to remove slight tendencies to spark, so that the contacts remain uninjured for long periods. Springs keep the contacts open when the rectifier is not in operation, thus preventing battery discharge through these contacts. This rectifier delivers current to the battery in the right direction regardless of the connections to the battery, because the battery polarizes the armature; no attention need be paid to polarity when making

these connections, because both half waves are utilized. If the supply circuit is interrupted temporarily, the rectifier restarts automatically when the current is restored.

9. In Fig. 4 is illustrated another type of vibrating rectifier with the cover raised. Fig. 5 shows one vibrator in greater detail, and Fig. 6 shows connections. Current enters through a small transformer, which reduces the voltage to that required for the batteries. The secondary of this transformer feeds directly into the batteries through an automatic cutout and a

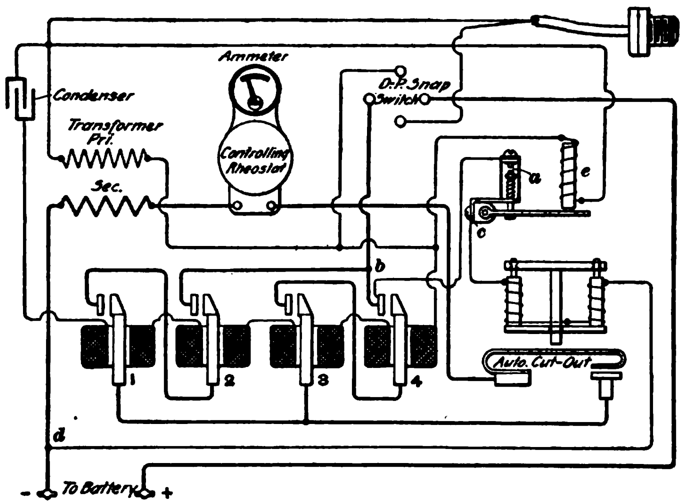


FIG. 6

series of contacts *1*, *2*, *3*, and *4* that vibrate in synchronism with the current in the circuit, so that only the positive current waves reach the battery.

Each vibrator, as shown in Fig. 5, consists of a permanent magnet, an alternating-current magnet coil, vibrating steel armatures that carry massive removable carbon contacts, and a stationary copper contact with a comb top for heat radiation. The magnet coils, with a condenser in series, are connected across the primary circuit, as shown in Fig. 6. The combined effect of the permanent magnets and the alternating magnetism of the coils causes the armatures to vibrate in synchronism

with the current in the coils. The polarity of the vibrator changes in synchronism with the current, and the poles of the permanent magnet alternately attract and repel the vibrator as its polarity changes.

The operating coils of the automatic cut-out are in series with contacts *a* across the battery, the circuit from the + battery terminal being switch–*b*–*a*–*c*–cut-out magnet coils–*d*. Relay *e* is connected across the primary circuit, and when the rectifier is operating the relay core is held up, allowing contacts *a* to close the circuit through the cut-out magnet. The core of this magnet is drawn down, holding the cut-out closed. On failure of voltage, contacts *a* open and allow the cut-out to open, thus preventing battery discharge through the secondary coil of the transformer.

This rectifier utilizes only the positive-current waves, giving a current curve similar to Fig. 3, except with the alternate half waves omitted. In making connections to the battery, care must therefore be taken to have the polarity correct.

ELECTROLYTIC RECTIFIERS

10. Electrolytic rectifiers are also practical in small capacities; they are used for charging storage batteries, for electrotyping and electroplating, and for operating search-lights, electric bells, clocks, railway signals, etc., all on a comparatively small scale.

The electrolytic rectifier is of the valvate nature, and consists of a stoneware or metallic vessel containing an electrolyte solution in which are placed electrodes. Ordinarily, the solution is sodium or ammonium phosphate, or sodium bicarbonate. Three electrodes are commonly used, two of aluminum and one of some other conductor, such as lead, carbon, iron, or steel, that is not readily acted upon, or corroded, by the electrolyte.

11. Aluminum in such a combination possesses the peculiar property of building up a surface film that permits current in only one direction, namely, through the electrolyte to the aluminum, but not from the aluminum to the other electrode.

In other words, the action of this film is analogous to that of a valve. By connecting the aluminum electrodes *a* and *b*, Fig. 7, to two terminals of an autotransformer, or to the secondary terminals of a two-coil transformer, the other electrode *c* to the negative terminal of a direct-current device, such as a storage battery, and the positive terminal of the device to the middle terminal of the autotransformer, direct current will be established in the consuming device when alternating voltage is applied to the autotransformer.

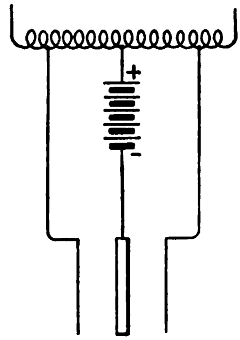


FIG. 7

The voltage between the aluminum terminals, and, consequently, the voltage between the storage-battery terminals, can be adjusted by changing the relative positions of the autotransformer leads. The current through the battery is regulated both by adjusting the voltage across the terminals of the aluminum electrodes and by adjusting the resistance in circuit with them. This resistance is sometimes adjusted by raising or lowering the aluminum electrodes in the electrolyte.

DESCRIPTION OF MERCURY RECTIFIERS

12. Nature.—The **mercury rectifier** also is of the valvate nature; it converts alternating current to direct current by means of an electric arc through mercury vapor. The essential part is a *bulb*, or tube, which is usually of glass with conductors that are sealed in the walls, and lead to electrodes inside. Pools of mercury, or quicksilver, in the bottom of the vessel form part of the electrodes, and above them are two other electrodes of graphite or iron suspended in separate chambers. The air is exhausted as completely as possible from the vessel, which is then hermetically sealed. The suspended electrodes are positive, or anodes; one mercury pool serves as the negative electrode, or cathode, and the other (or both others if there are two) serves as the starting anode.

13. Construction.—Fig. 8 illustrates a typical arrangement. The anodes, which may be of iron, graphite, or any substance that will not amalgamate (combine in an alloy) readily with mercury are shown at *a* and *b*; the mercury pool serving as negative electrode or cathode is shown at *c*; and the mercury pool serving as the auxiliary positive electrode for starting only, at *d*.

These vessels assume various forms, depending on the designer and on the service for which they are intended. The anodes must be far enough from the mercury, and so protected by the shape of the vessel, that mercury cannot spatter on them, although they are continuously in an atmosphere of mercury vapor.

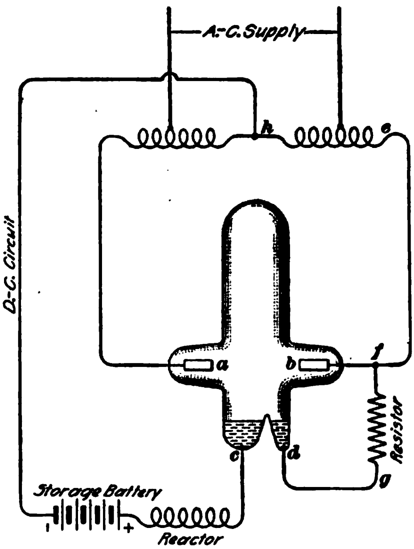


Fig. 8

14. Connections.—Fig. 8 shows simplified connections also. The anodes *a* and *b* are connected with terminals of an autotransformer; the cathode *c* is connected through a reactor with the positive terminal of a storage battery, and the starting anode *d*, through a resistor with one of the autotransformer terminals. The negative terminal of the storage battery is connected with the middle terminal of the autotransformer, and two additional autotransformer terminals are connected with a single-phase circuit (A.-C. supply).

With alternating current in the autotransformer, an electromotive force exists between the anodes *a b* and *d* and the cathode *c*; *a* and *b* are alternately positive to *c*, and the polarity of anode *d* agrees with that of anode *b*. By tilting the vessel slightly, the two mercury pools join, and alternating current is

set up in the path *e–f*–resistor–*g*–*d*–mercury–*c*–reactor–storage battery–*h*, this current being limited by the resistance of the path. Righting the vessel opens the circuit by separating the two mercury pools and causes a spark at the separation. This spark starts the operation, current passing alternately from anodes *a* and *b* to cathode *c*, and thence through the reactor and the storage battery back to the autotransformer, always in the same direction through the battery or other direct-current device.

15. Theory.—Any conductor serving as a negative electrode, possesses, to some extent, an initial resistance that disappears as soon as current begins. Mercury, zinc, cadmium, and some other metals, especially the first mentioned, manifest this quality to a marked degree. This cathode resistance, which appears as an insulating film over the surface of mercury, is enormously increased in a vacuum. It is broken down completely by a hot spark or an arc, and remains absent while electricity is flowing to the mercury as the negative electrode, but forms again instantly when the current ceases. Without the aid of a starting spark, very high voltage, ranging from 6,000 to 25,000, would be required to break down this cathode resistance. Shaking the vessel so as to form ripples over the surface of the mercury assists high voltage to start current under such conditions.

After the current has started to the cathode, it must continue as long as operation is desired. The arc from one anode must begin before that from the other ends; otherwise, the cathode resistance will reestablish itself and the operation will cease entirely. The brief instant during which alternating current is passing through zero value is sufficient for this resistance to be reestablished. Means must therefore be provided for continuing the current from each anode during the instant of reversal until the other anode becomes positive. In practice, this provision consists of reactance in the direct-current circuit, either in the form of a special reactor coil, or as a property of the autotransformer. Enough energy is stored in the reactance to carry the arc past the zero point in the current wave. Fig. 8

indicates the use of special reactance, but the combination of this property in the autotransformer is very common.

16. Operation.—The nature of the current from a mercury rectifier will be more clearly understood on referring to Fig. 9. The current in one of the anodes is represented by the curves *a*, in the other by the curves *b*, the resultant rectified current through the direct-current circuit by curve *c*. Curve *d* represents the electromotive force impressed on the anodes.

The rectifier reverses alternate half waves of current, so that all half waves are in the same direction from the zero line as shown at *a* and *b*, Fig. 9; also, the resultant direct current is not absolutely smooth, but of a wavy or fluctuating nature, as shown in *c*; that is, it is a *pulsating* direct current The extent of these waves can be modified by the use of more or less reactance in the direct-current circuit. For many uses, a pulsating direct current is not objectionable; for charging storage batteries, such a current is thought to have some advantages.

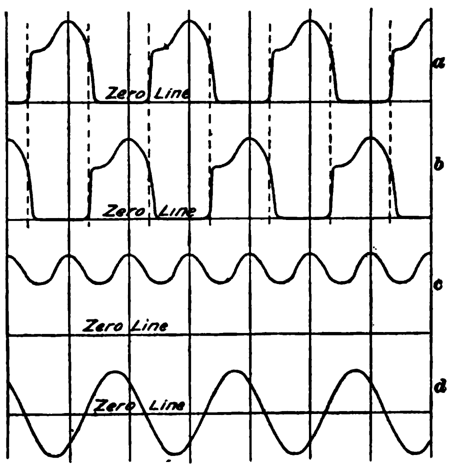


FIG. 9

The effect of reactance can be seen in the peculiar shape of the curves *a* and *b*. On account of the storage of magnetic energy in the autotransformer core, the current does not rise at a uniform rate to full maximum value, as is shown by the depressions near the tops of the curves. During the latter part of each current wave, this stored energy maintains the current until the other anode becomes positive and begins to deliver current. The dotted lines indicate where the downward slope of each curve continues just past the beginning point of the preceding half wave from the other anode.

17. Phenomena During Operation.—While the rectifier is operating, a glow of light fills the bulb and a specially bright spot appears on the surface of the mercury. This spot continually changes its position, dancing around over the surface of the mercury, which is agitated as if boiling. Condensation of the mercury vapor, together with small drops of mercury thrown off by the agitated surface, forms globules on the glass. These globules gather in drops and run back to the pools in the bottom.

The total electromotive force drop in a rectifier bulb does not vary with the current, but depends largely on the length and the diameter of the vapor path and the number of bends, or angles, in this path. A constant drop of approximately 5 volts occurs at the anodes, and a little less at the cathodes; the drop through the vapor path varies from 4 to 5 volts up to possibly 15 volts. The drop in the mercury vapor increases when the vapor pressure is increased, and decreases when the temperature is increased. The presence of gases, other than mercury vapor, increases the drop very materially; hence, all other gases are excluded as completely as possible. In commercial low-voltage bulbs for battery charging, the total electromotive force drop is approximately 14 volts at any current, and in high-voltage bulbs for arc lighting, approximately 25 volts.

18. Current Capacity.—The current capacity of a bulb depends on the size of the leading-in conductors, especially the platinum wires sealed in the glass, and on the cooling capacity of the bulb. The voltage drop being fairly constant, heat is generated practically in proportion to the current, and, for good operation, the surface of the glass must be large enough to radiate this heat and prevent an excessive rise of temperature. The condensing mercury carries the heat to the glass, from which it escapes through radiation and convection. Immersion in oil hastens the dissipation of heat; this method is employed for arc-lighting rectifiers as will be explained later.

Theoretically, mercury rectifiers can be made for any desired current capacity, but in practice the difficulty of producing and maintaining high vacuums of large size has limited the

current capacity to about 50 amperes. The extreme simplicity of the device and its low cost, compared with other rectifying devices, make its further development attractive. The present difficulties will doubtless be finally overcome and the application of mercury rectifiers for converting alternating current to direct current will become very general.

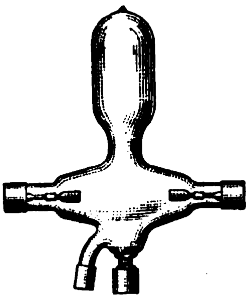


FIG. 10

19. Voltage.—The dimensions and the shape of the mercury path largely determine the direct-current voltage that a rectifier bulb can sustain and deliver. Fig. 8 and the discussion referring to it show that the electrodes serving as anodes are opposed to each other in polarity, and that if an arc should form across them, the autotransformer would be short-circuited. The forming of such an arc is prevented by the surface resistance of a negative electrode (see Art. 12) and by the length and shape of the vapor path. In practice, the anodes are so enclosed and protected that not a particle of mercury can spatter or fall against them; otherwise, the negative electrode resistance would be broken down and a short circuit would result. Hence, the longer, narrower, and more crooked the vapor path, the higher will be the voltage that can be sustained.

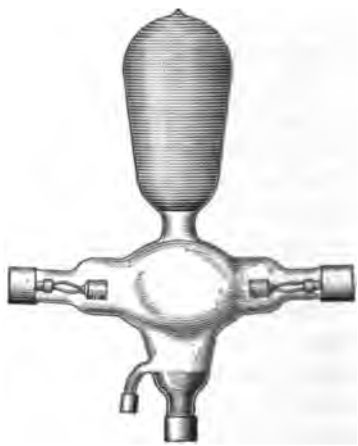


FIG. 11

20. Commercial Bulbs, or Tubes.—Fig. 10 shows a 5-ampere bulb for use on single-phase circuits. Standard rectifiers in which it is used are made for converting single-phase current at either 110 or 220 volts into direct current at 16 volts, maximum; 10-ampere bulbs of similar appearance are also available. Fig. 11 shows

a 30-ampere bulb for converting 110- or 220-volt single-phase current into direct current at 120 volts, maximum; 50-ampere bulbs for the same service have the same general appearance. Figs. 12 and 13 show, respectively, a bulb and a tube (manufacturer's choice of terms) for high-voltage work in series-arc lighting.

21. Efficiency.—The efficiency of high-voltage bulbs is higher than that of low-voltage bulbs, because the drop of voltage in the bulb is nearly constant and is therefore a smaller

FIG. 12

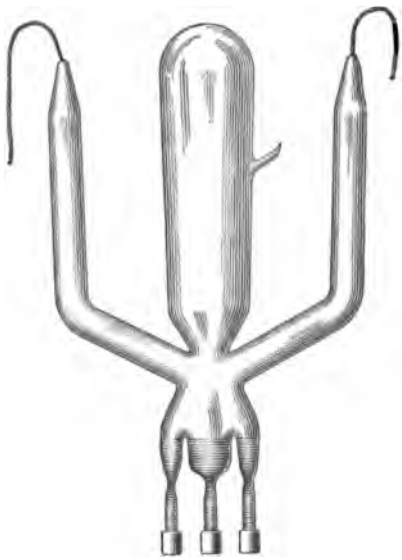


FIG. 13

percentage of the higher voltage. For example, when supplying a 14-volt battery circuit, the voltage drop in the bulb being 14, as before explained, the efficiency of the bulb cannot be over 50 per cent.; that is, the voltage loss in the bulb equals that supplied the circuit. If the voltage of the direct-current circuit is 134, the efficiency of the bulb is approximately $\frac{134}{134+14}$ $=.905$, or 90.5 per cent. On the other hand, the efficiency of a 3,500-volt bulb on a series-arc circuit is very high, the voltage

loss being less than 1 per cent. of the total direct-current voltage.

22. Rectifier bulbs, or tubes, are commonly used on single-phase circuits, and therefore have only two anodes; three anodes could be provided, however, and the bulb could be used on three-phase circuits. In this case, the direct current would be less pulsating because of six half-wave peaks instead of two on a single-phase circuit. Three-phase mercury rectifiers are very little used.

APPLICATIONS OF MERCURY RECTIFIERS

CHARGING STORAGE BATTERIES

23. Mercury rectifiers are used to charge storage batteries, to operate arc lamps and moving-picture machines, for electrolytic work and electroplating, and in a few cases, for operating small direct-current motors. The chief uses are charging storage batteries and operating arc lamps.

Probably the largest field of application is to charge storage batteries. Batteries that can be economically charged by such rectifiers are those used for automobile motors and lights, motor boats, ignition for internal-combustion engines, telephone and telegraph service, signal and alarm systems, electric clocks, railroad car lighting, and chemical work. Among these several uses, charging automobile batteries is chief. This work in both public and private garages, employs many rectifiers.

24. Mercury rectifiers for battery charging are made *non-automatic starting* and *automatic starting*. The former requires attendance both at the initial start and to start again after stoppage due to overload, temporary voltage failure, or other cause. The automatic type starts again without attention after each failure until the charge is completed, when, if the conditions of the battery and the supply circuit are suitable, the operation ceases automatically. The automatic type is therefore superior where constant attendance is impracticable.

Commercial practice is to supply both types complete with rectifier bulb or tube and all necessary transformers, dial switches for adjusting the voltage, starting switch, circuit-breakers, fuses, etc. All the auxiliaries are compactly mounted and furnished with the necessary mechanical protection. The rectifier bulb is mounted upright in a pivoted holder arranged for tilting by hand or automatically, and for returning automatically to the upright position when released.

The dial switches afford a means of changing connections

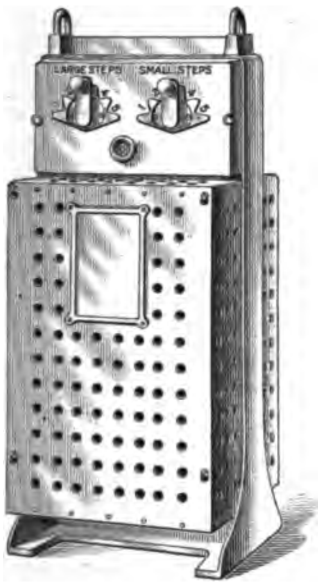


FIG. 14

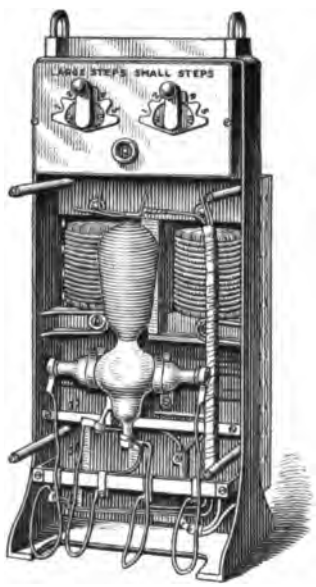


FIG. 15

with the transformers so as to raise or lower the direct-current voltage. This adjustment must be made approximately correct before operation can start. The correct adjustment depends on the number of cells to be charged in series, and to some extent, on their condition. If the battery is in good condition, the voltage at the beginning of the charge should be about 2.15 per cell, and at the end 2.55 per cell.

In starting the non-automatic type, the alternating-current and the direct-current circuits are closed, a hand-operated

starting switch is moved by the operator to the running position, and the bulb is tilted until the arc starts. The starting switch is then released, and it returns automatically to the running position. In some cases, the starting switch is so connected with the tilting mechanism that closing the switch in the starting position automatically tilts the bulb. While a non-automatic rectifier is operating, an attendant must be present.

25. Example of Mercury Rectifier for Battery Charging.—Figs. 14 and 15 show a 30-ampere mercury rectifier arranged for automatic starting; the handles of the two dial switches and the hand wheel for closing the circuit-breaker contacts are plainly shown in both views. This particular rectifier is typical of the product of one manufacturer only, but it will serve to illustrate all rectifiers for battery charging. It is automatic in that an electromagnet is arranged to tilt the bulb when the magnet is excited. This tilting mechanism is controlled by a relay on the back of the panel; the relay acts also as a circuit-breaker, opening both the alternating-current and direct-current circuits if the current in the latter becomes too high. Owing to the action of the tilting mechanism, this rectifier is automatically restarted if the arc goes out before a charge has been completed.

26. Fig. 16 shows the **connections** of this mercury rectifier. The two 5-point dial switches are so connected to the autotransformer and reactor taps as to give voltage adjustments to suit different numbers of cells. One dial adjusts the voltage in five coarse steps, and for each one of these steps the other dial gives five possible intermediate adjustments, making twenty-five total steps available.

One side of the alternating-current circuit is connected through circuit-breaker contacts *a* with a contact on the coarse-step switch, and the other side with the reactor, which, in, turn is connected with three contacts of the coarse-step switch. The autotransformer is provided with thirteen leads, six of which are connected with contacts on the coarse-step switch and six with contacts on the fine-step switch, the middle lead

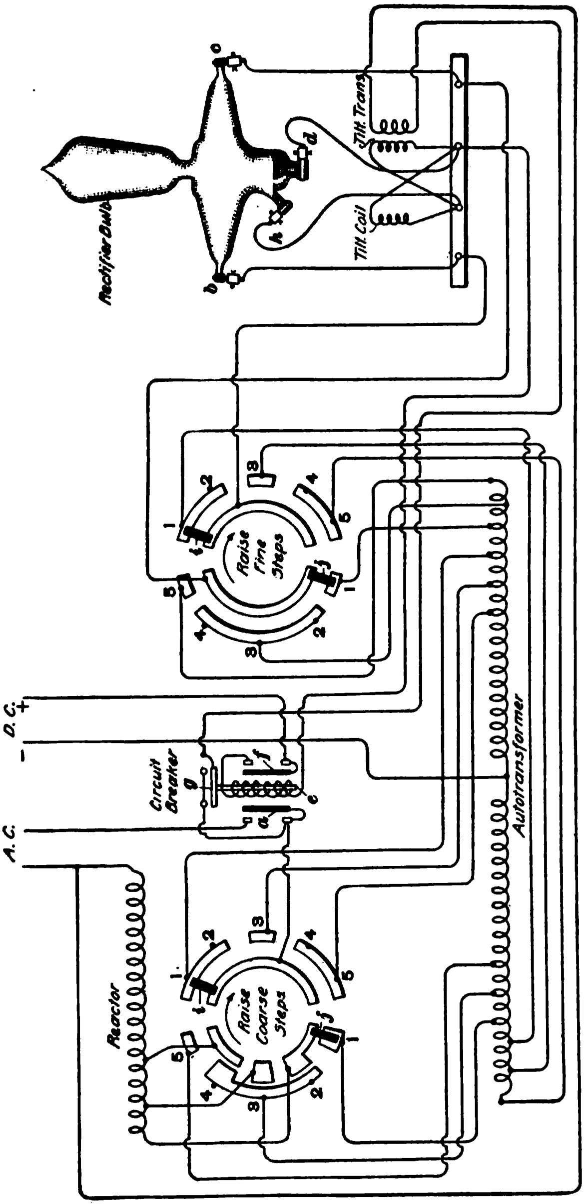

Rectifier Bulb
Tilt Trans.
Tilt Coil
Raise Fine Steps
Raise Coarse Steps
Circuit Breaker
Autotransformer
Reactor
A.C.
D.C.

FIG. 16

serving as the negative terminal of the direct-current circuit. The anodes *b* and *c* of the rectifier bulb are connected with the two main contacts on the fine-step switch; the cathode *d* is connected through the trip coil *e* of the circuit-breaker with one of the circuit-breaker contacts, which is joined through contact *f* with the positive terminal of the direct-current circuit. The primary coil of the small tilting transformer is connected between a contact *g* on the circuit-breaker and one side of the alternating-current circuit. The secondary coil is connected with points that serve as terminals of the two mercury electrodes *d* and *h* and also as terminals of the tilting coil.

In Fig. 16 the plunger of the circuit-breaker is shown drawn down, a condition that prevails only when the rectifier is operating, that is, with current in the trip coil *e*. At other times, a counterweight holds the plunger at the upper limit of its travel, closing the contacts *g* and placing the primary of the tilting transformer in series with the main circuit-breaker contact *a*.

The dial-switch stationary contacts are represented by sections of concentric rings, and the successive points of each switch are indicated by *1*, *2*, *3*, etc. The moving contacts *i* and *j* are mounted under the ends of a lever pivoted at the center of the circles; these contacts connect adjacent stationary contacts of the two circles. Both dial switches are shown in position for the lowest voltage adjustment; rotating them clockwise raises the voltage, one by large steps and the other by small steps.

27. In **operating the rectifier,** it is started by adjusting the dial switches to give the desired voltage as nearly as possible; the circuit-breaker contacts *a* and *f*, Fig. 16, are then closed by turning the knob on the front of the rectifier case, and finally the line switch in the supply circuit is closed. Alternating current is thus set up in the path *a*–*i*–autotransformer–*j*–reactor, and also in the path *a*–*g* (which is closed until current is set up in *e*)–tilting transformer. Anodes *b* and *c*, being connected through the fine-step switch with the autotransformer winding, are thus subjected to alternating voltage, and the secondary voltage of the tilting transformer is applied between

the terminals of the tilting coil and between the mercury electrodes *d* and *h*. The resulting current through the tilting coil causes the bulb to tilt until the mercury electrodes join and short-circuit the tilting coil. The bulb then returns to the vertical position, breaking the mercury connection between the two lower electrodes and causing a spark.

28. If the arc starts from either electrode *b* or *c*, Fig. 16, to the cathode *d*, direct current is established in the circuit, including coil *e* of the circuit-breaker, and the tilting-transformer circuit is automatically opened at contact *g*, thus stopping further tilting. If the arc does not start promptly, the

FIG. 17

FIG. 18

tilting continues until a correct start is made. While the rectifier is operating, too much current through the circuit-breaker coil draws the plunger down hard, trips a latch, and releases the breaker, thus giving overload protection. If the line voltage fails temporarily, or if the arc stops accidentally for any other reason before the current has fallen to less than 10 amperes, the circuit-breaker plunger rises promptly and closes contact *g*; the return of voltage then causes the bulb to tilt automatically and restore the arc.

If, however, the current falls gradually, the counterweight of the circuit-breaker plunger slips back slowly until its rod

is engaged by a latch, leaving contact *g* open and preventing further tilting. This feature is utilized in some cases to charge batteries during the night. The rectifier is adjusted for correct voltage at the beginning of the charge; as the battery voltage rises, the charging current decreases until it becomes so low that the arc goes out. This method of automatically terminating a charge can be depended on only when a battery is in good condition and the supply voltage is constant, conditions that seldom prevail in practice.

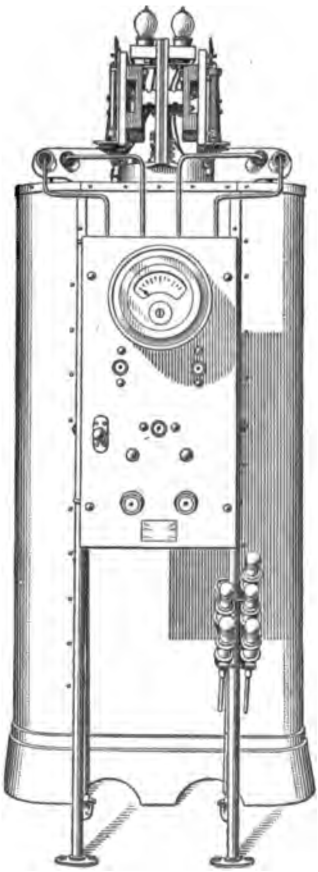


Fig. 19

29. The **automatic discontinuance of operation** on gradual failure of current prevents repeated tilting after a charge has terminated. When the battery current falls to 5 or 6 amperes, the arc is no longer sustained, and were it not for the latch that automatically catches and holds the slowly rising circuit-breaker plunger, the bulb would continue to tilt until an attendant arrived and opened the breaker. This repeated tilting would be undesirable from a mechanical standpoint, even though the device might be safe, electrically, from injury.

A better plan to end operation automatically, is by the use of a *time switch*. Figs. 17 and 18 show a form of such a device, which consists of a single-pole circuit-breaker in a cast-iron case and arranged to be tripped by an alarm clock. The alarm is set to go off at the time operation should cease, and the clock is pushed back into place.

When the alarm mechanism operates, it releases the circuit-breaker, which opens the circuit. The clock can be set to discontinue charge before it is fully completed, and an attendant can then supervise the completion in a comparatively short time.

OPERATING ARC LAMPS

30. Direct current is superior to alternating current for operating some types of arc lamps, especially those of the metallic-flame type, while alternating current has advantages even more striking for transmitting and distributing energy.

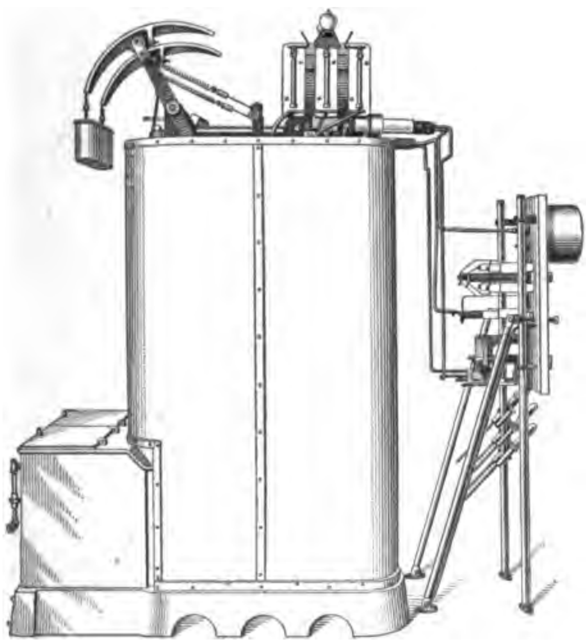


FIG. 20

The mercury rectifier operating in conjunction with a constant-current regulating transformer offers a ready means of gaining the advantages of both alternating-current distribution and direct-current arc lamps.

As the essential parts and the main features of operation of rectifiers for series-arc circuits are the same, a description of one make will give a good idea of the construction and operation of all. Fig. 19 shows the front of a combined unit, series mercury-arc rectifier set consisting of a constant-current transformer, a direct-current reactor, a tube tank, and an exciting transformer mounted on one base with the switchboard in the foreground, and Fig. 20 shows a side view of this device.

31. Rectifier Outfit for Arc Lighting.—The constant-current transformer shown in Figs. 19 and 20 is of the air-cooled type. Its core and coils appear as shown in Fig. 21, and its assembly, as shown in Fig. 22. The method of counter-

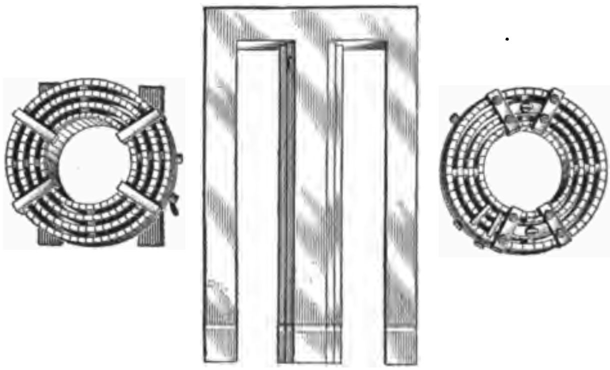


FIG. 21

balancing the primary coils is such that their distance from the fixed secondary coils changes automatically with each change of secondary current. This movement adjusts the magnetism through the secondary coil so as to keep the secondary current nearly constant.

The tubes are in carriers submerged in oil in a separate tank adjacent to the transformer tank. This oil is kept cool by circulating water through coils of pipe inside the tank. The tubes are easily removed, as shown in Fig. 23. Rectifier outfits are also made for arc lighting, in which the transformer coils and the bulbs are oil-immersed in one tank, the oil being cooled by circulating water in coils of pipe.

32. An indicating lamp in series with each tube or bulb on or near the rectifier outfit informs the operator whether the tube is operating. Reactors in each circuit smooth out current pulsations; static discharges and lightning arresters with each outfit protect from injury by heavy electrical stresses. Exciter transformers furnish low-voltage current to start the arc. A magnet controlled by a hand-operated switch is provided for shaking or rocking the tube without opening the case.

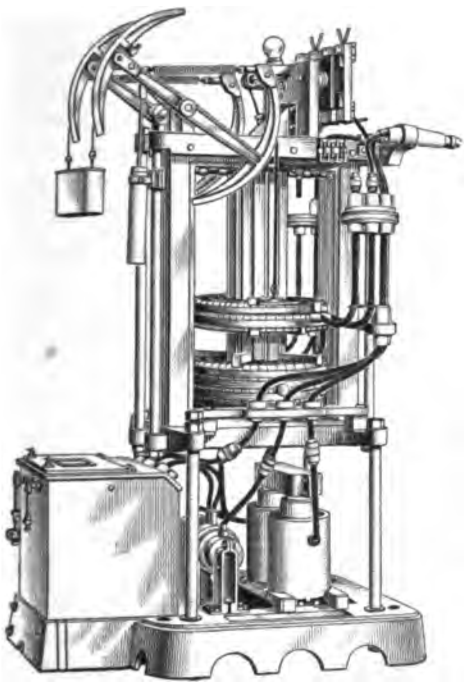


FIG. 22

FIG. 23

The indicating lamps and static dischargers are mounted on top of the transformer, as is shown in Figs. 19, 20, and 22. The exciting transformers and reactances are mounted under the main transformers, as in Fig. 22.

Series mercury-arc outfits are made for 4- and 6.6-ampere circuits with twenty-five, fifty, and seventy-five lamps in series.

The outfit just described is for a 50-lamp circuit, the two tubes operating in series. Single outfits are also in use with two bulbs, each supplying a separate and distinct fifty-lamp circuit.

OPERATING MOVING-PICTURE MACHINES

33. Mercury rectifiers are especially successful in supplying direct current for operating moving-picture machines. The direct-current arc gives clearer, whiter, steadier, and stronger light on the screen than can be obtained with equivalent energy in the form of alternating current. If direct-current lighting circuits are available, they are usually at voltages much higher than are needed for the moving-picture machine, necessitating much loss in regulating resistance. Lighting circuits, however, usually carry alternating current, and by means of the mercury-arc rectifier the advantages of the direct-current arc can be obtained without excessive loss, the current being regulated by means of transformers and choke coils.

ALTERNATING-CURRENT MOTORS AND SYNCHRONOUS CONVERTERS

POLYPHASE INDUCTION MOTORS

ESSENTIAL MEMBERS

1. Rotative devices driven by alternating-current energy are *induction motors*, *synchronous motors*, and *synchronous converters*, each of which has its field of usefulness.

2. Because of its simplicity, economy, and durability, the **induction motor** is far more commonly used than any other type of motor for industrial purposes. An induction motor consists of two essential members, the *primary*, which is connected to the electrical circuit, and the *secondary* in which electric currents are induced by the magnetic flux produced by the primary currents. Generally, though not necessarily, the primary is stationary and receives electrical energy, which is transformed into mechanical energy in the rotor or secondary.

Other names commonly applied to the primary are *stator* and *field*, and to the secondary *rotor* and *armature*. Primary and secondary usually relate to electrical performance, and the other terms to mechanical features. In this Section the terms primary and secondary are generally used, as they more clearly describe the electrical functions of these parts. Induction motors are made for operation on polyphase and single-phase circuits.

POLYPHASE MOTOR PRIMARIES

3. Construction.—The **primary,** or *field,* of an induction motor is practically the same in construction as that of the stationary armature of an alternator. Induction motors, however, are generally smaller than alternators. Fig. 1 shows the general appearance of the primary for a polyphase motor.

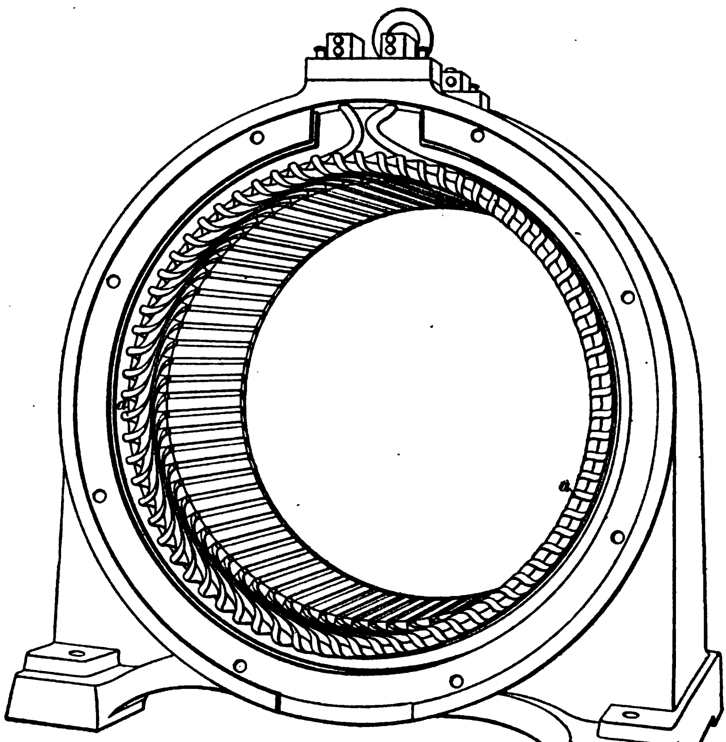


Fig. 1

A laminated core with slots in the inner face is clamped between plates held together by rivets, bolts, keys, or other means, according to the design. The core may be assembled in a frame, as in the illustration, or it may be provided simply

with supporting feet attached to the clamping rings, or end shields, as in Fig. 2, the central part of the core being exposed. The core punchings are here shown assembled in bunches and shaped to present more cooling surface to the air.

Coils *a*, Fig. 1, are assembled in slots, which are usually open at the top, with notches for wedges, as explained in connection with alternators. In such cases, the coils are held in place by wooden or metal wedges. Some induction-motor primaries are made with slots partly closed at the top, and, in assembling, the coils are passed through the narrow openings.

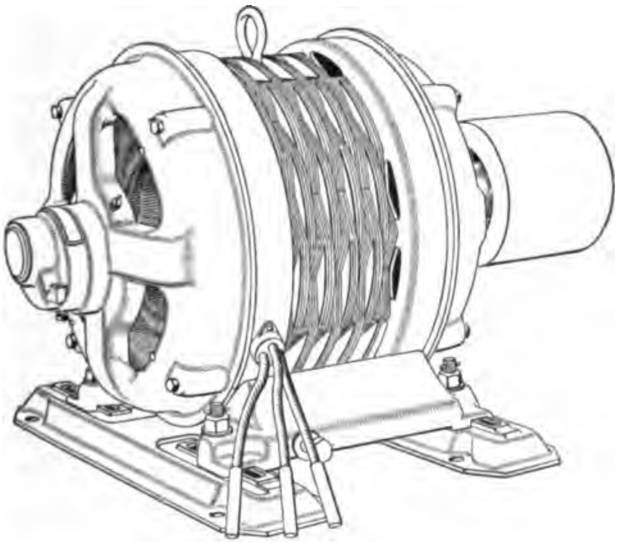


FIG. 2

4. Rotating Magnetic Field.—The rotative effort, or torque, of every induction motor depends on the fact that magnetic poles caused by the alternating currents in the primary windings revolve about the center, giving the effect of a rotating magnetic field, or flux; that is, the torque is caused by the rotating flux. If the field frame of a direct-current motor were rotated with the field excited, the flux in sweeping over the armature conductors would induce electromotive forces in them. If the brushes were lifted from the commutator

and all the bars short-circuited by a metal ring, currents would be established in the armature conductors, and the reaction between these currents and the magnetic flux would cause the armature to rotate in the same direction as the field frame. Exactly the same effect occurs in an induction motor, but without any movement of the primary coils or core, simply a revolution of magnetic flux.

Fig. 3 illustrates the principle of the rotating flux. Conductors *a* and *b* short-circuited by end pieces *c* and *d* represent one element of an induction motor of which *e e* represents the shaft and *N* and *S* two magnetic poles revolving in the direction indicated by the long arrow. These poles do not represent a revolving part of the machine, but simply revolving north and south magnetic poles. Currents are induced in the conductors in the directions indicated by the short arrows, and these currents induce a south pole on the face of the loop *a d b c*, adjacent to the revolving north magnetic pole and a north pole adjacent to the revolving south pole. The motor element is thus drawn around by magnetic attraction of the revolving poles.

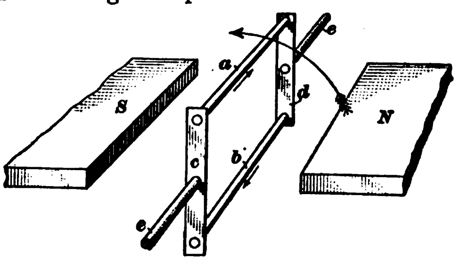


FIG. 3

5. Theory of Rotating Field.—The theory of the rotating field, or revolving magnetic flux, of an induction motor will be more clearly understood by reference to Fig. 4, in which *A* and *B* represent two closed coils at right angles to each other, and curves *A′* and *B′*, two-phase currents. It should be understood that the currents in the coils vary as represented by the curves, giving varying conditions of polarity in the two coils, as indicated at positions *1*, *2*, *3*, etc. The coils do not move; the different positions merely indicate different current and polarity conditions.

At position *1*, the current in coil *A* is 0 and that in coil *B* maximum negative, as shown by the curves *A′* and *B′*. The

polarity of the coil *B* is indicated by short arrows, and the resulting polarity of the two coils, by the longer arrow; in this case, the arrows agree in direction, because coil *A* carries no current. In position *2*, each coil is carrying the same current, that in *A* being positive and that in *B* negative, as shown by the curves. The resulting polarity, as indicated by the longer arrow, is now 45° counter-clockwise from the first position. In position *3*, the current in *A* is maximum positive and that in *B*, 0, the resulting polarity is 45° farther counter-clockwise. The remaining positions show that as the current continues its cycle of changes the resulting polarity of the two coils

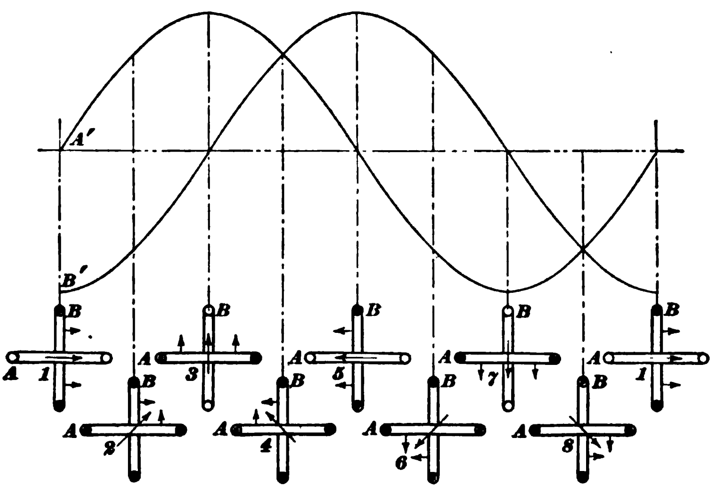


FIG. 4

continues to rotate counter-clockwise and that one rotation is completed per cycle. Either two-phase or three-phase currents in suitable windings on an induction-motor primary causes a rotating magnetic field, according to this principle.

If the connections of one phase are reversed, the direction of rotation is reversed. For example, if the current in coil *B* were reversed, curve *B'* would be maximum positive when *A'* is *0* and *0* when *A'* is maximum positive, and so on. The polarity of winding *B* would then be reversed in every case, and the resulting polarity of the two windings would rotate clockwise.

6. Synchronous Speed.—The primary windings of an induction motor are arranged and connected for a given number of pairs of poles, as explained in connection with alternators. Any magnetic pole makes one complete revolution in the field structure in as many cycles as there are pairs of poles. If f represents the frequency, in cycles per second, and n the number of pairs of poles, the number of revolutions of the magnetic poles per second is $f \div n$ and the revolutions per minute, or *synchronous speed*, is $\frac{60\,f}{n}$

When the speed of a motor is in accordance with this formula, the motor speed is said to be synchronous with that of the alternator, or the motor and alternator are said to run in synchronism.

7. Slip.—The flux of the magnetic poles cuts across the secondary conductors and induces in them the current that causes the secondary to rotate. If the secondary were rotated at synchronous speed, its conductors would not cut the flux and no turning effort, or torque, would be exerted. The secondary therefore rotates at enough less than synchronous speed to allow the required current to be induced in its conductors. The difference between synchronous speed and the speed of the secondary is called the *slip* of the motor. Slip is nearly always expressed in per cent. of synchronous speed. Thus, according to Art. 6, the synchronous speed of a four-pole sixty-cycle induction motor is $\frac{60\,f}{n} = \frac{60 \times 60}{2} = 1{,}800$ revolutions per minute; if the speed of the motor secondary is 1,710 revolutions per minute, the slip is $\frac{1{,}800 - 1{,}710}{1{,}800} \times 100 = 5$ per cent. The full-load slip of commercial induction motors for general service ranges from possibly 8 per cent. in small motors to 2 per cent. in motors of 100 horsepower and larger.

8. Variation of Slip With Torque.—The torque must be great enough to make the secondary rotate. As the torque depends on the current in the secondary conductors, and this

current depends on the rate of cutting lines of force, the slip while the motor is running, automatically adjusts itself according to the torque required. If the load increases, necessitating greater torque, the slip increases accordingly; if the load decreases, the slip decreases. The slip at no load, that is, with the motor running idle, is very low, the speed of the secondary being very nearly synchronous.

9. Effect of Secondary Impedance on Slip.—The induced currents in the secondary conductors vary directly with the electromotive forces induced in the conductors and inversely with the impedance of the conductors and their interconnections. As the secondary currents must be enough to cause the required torque, the induced electromotive forces must be greater in a secondary having high impedance than in one with low impedance; that is, the slip depends also on the secondary impedance.

10. Direction of Rotation.—The direction of rotation of an induction motor agrees with the direction of rotation of its magnetic field, and can be reversed by interchanging the connections of one phase of the primary.

POLYPHASE MOTOR SECONDARIES

SQUIRREL-CAGE ROTORS

11. Induction-motor secondaries, or **rotors,** are of the *squirrel-cage type* and the *coil-wound*, or *phase-wound type*, either of which can be used in the same primary. The motors are designated, according to the type of rotor used, as *squirrel-cage motors*, and *phase-wound motors*.

Fig. 3 shows an element of a squirrel-cage rotor, straight bar or rod conductors short-circuited at the ends. Fig. 5 shows a complete squirrel-cage rotor, in which the conductors *b* are bolted to end rings *r*. The conductors and end rings have the general form of a squirrel-cage wheel, which fact gives the rotor its name. As its resistance is not adjustable, it might also be called a *constant-resistance rotor*.

12. Construction.—The construction of a squirrel-cage rotor is very simple. A laminated iron core is assembled on a cast-iron spider, which is pressed on a shaft and keyed. In some cases, especially with small motors, the core is assembled and keyed directly on the shaft, the spider being omitted. The core is clamped between end plates secured to the spider or to the shaft, and is provided with slots in the outer periphery. Straight copper bars or rods are placed in these slots, and the ends of the bars are fastened to rings. The bars are usually

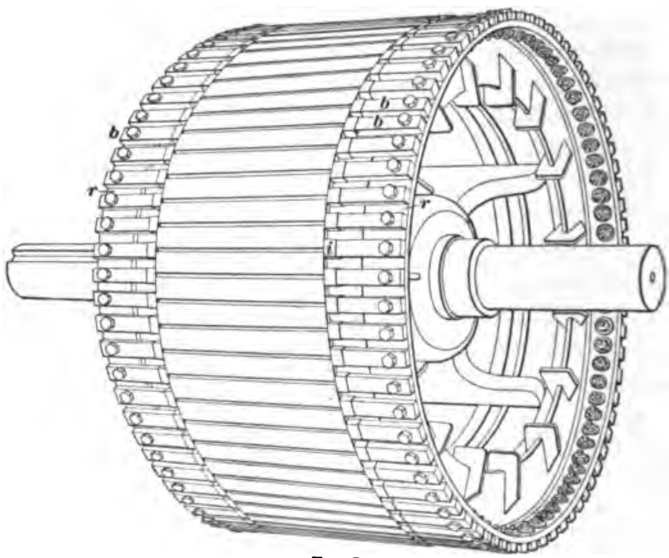


FIG. 5

not insulated from the iron, because most of the current follows the bar rather than the higher resistance laminations. In some cases, a piece of thin paper is wrapped around each bar, as at *i*, Fig. 5; insulating cement is sometimes used instead of paper, making the rotors impervious to moisture and capable of withstanding great heat.

13. Among the methods used to fasten the bars to the end rings are bolts, bolts and solder or solder alone, keystone construction, welding, cast-on end rings, and closed-coil construction. The high temperatures at the rings are liable to

loosen bolts and solder, especially in heavy service. In the keystone construction, the conductors are thrust through holes in edgewise end rings (planes perpendicular to the shaft) and

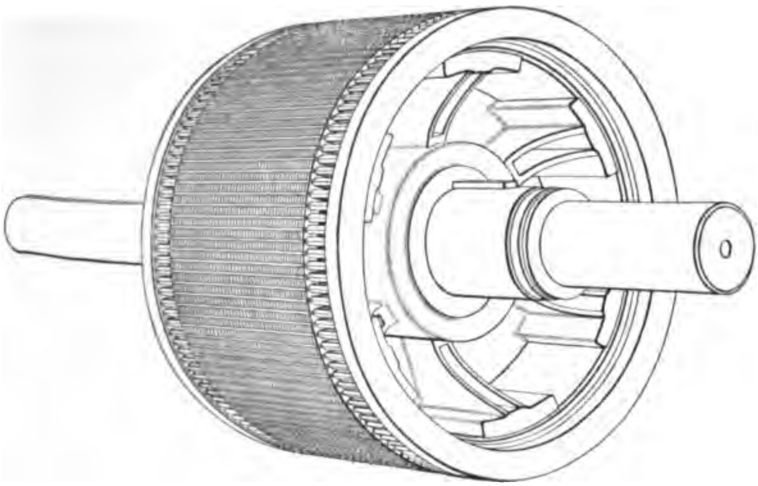
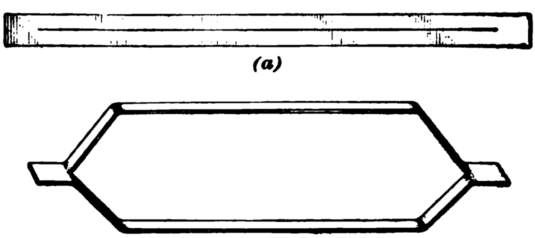


FIG. 6

then keyed in place. Welding the bars to the rings makes very durable construction, as does also casting solid rings on the ends of the bars, as in Fig. 6. Closed coils are sometimes installed instead of the strictly squirrel-cage construction, and



(a)

(b)

FIG. 7

with these coils no end rings are necessary. Copper strips are slit lengthwise through the center, except a small part at each end, as in Fig. 7 (*a*), and the sides are drawn apart as in (*b*).

14. Starting Squirrel-Cage Motors.—When an induction motor is first connected with a source of alternating current, and before the secondary begins to rotate, the slip is 100 per cent.; the momentary current taken from the line would be several times full-load current unless some means were taken to limit the starting current. Squirrel-cage induction motors up to and including 5 horsepower are usually started by switching them directly on to the line, but larger sizes are provided with some form of starting device. This device may be a *resistance starter* or an *autotransformer starter*.

15. Resistance starters are recommended by some manufacturers for polyphase induction motors of from 5 to 25 or 30 horsepower. They consist of non-inductive resistances arranged for connection in two phases of the primary circuit and for being cut out in steps as the motor speed accelerates, very much the same as operating a direct-current motor starter. This resistance limits the starting current to a safe value until the motor speed accelerates and reduces the slip. Fig. 8 shows a typical resistance starter for induction motors. The same type of starter can be used for either a two-phase or a three-phase motor, although the resistances are different. The use of only two resistances in starting a three-phase motor slightly unbalances the phases, but not enough to cause difficulty with the size of motors using such starters. Automatic low-voltage release devices are frequently employed on these starters.

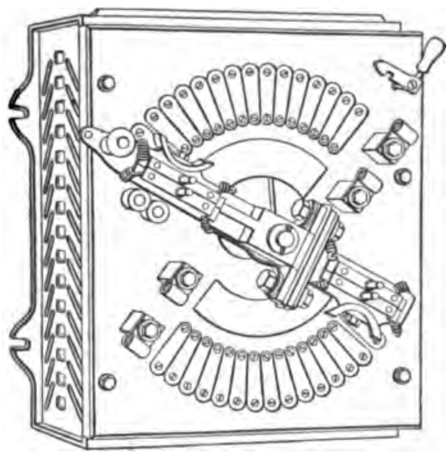


FIG. 8

16. Autotransformer starters, variously called *auto-starters* and *compensators*, consist of autotransformers with

switching devices so arranged that reduced voltage can be impressed on the motor primary for starting. By the principle of the autotransformer, the current in the motor primary is increased over the current taken from the line in approximately the same ratio as the starting voltage is decreased from the line voltage. This fact gives the autotransformer starter a possible advantage over the resistance starter, since with the latter the line current and the motor current are the same.

17. Fig. 9 shows the connections of a starting compensator with a three-phase squirrel-cage induction motor. The

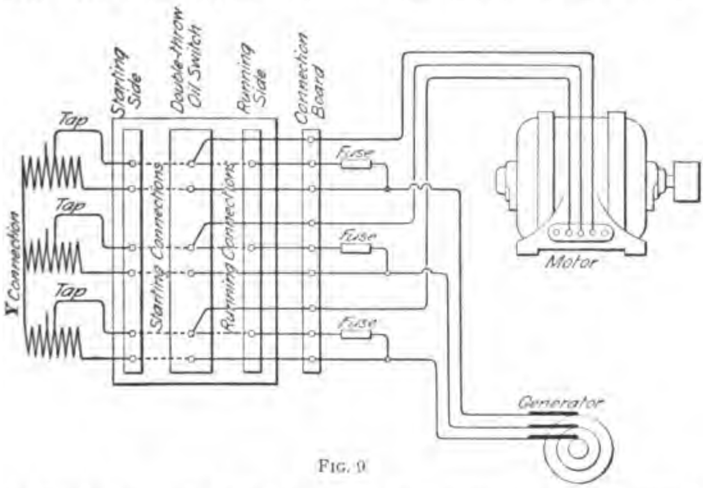


FIG. 9

double-throw switch with contacts immersed in oil can be moved from its *off-position* first to the *starting position* and then to the *running position*.

In the off-position, both autotransformer and motor windings are disconnected from the line. In the starting position, the switch connects the line to the ends of the autotransformer winding and the motor to the taps, without breakers, or fuses, in circuit. In the running position, the autotransformer winding is cut out and the motor is connected to the line through fuses or overload relays. To prevent the attendant from throwing the motor directly on the line, thereby causing a rush of current, which the autotransformer is designed to avoid,

an automatic latch is provided. This latch is so arranged that the lever can not be thrown from the off-position directly into the running position; it must first be moved into the starting position (backward) and from there into the running position (forward) by a quick throw of the lever, thereby avoiding any appreciable drop in speed and consequent increase in current in passing from the starting into the running position. If moved too slowly from the starting to the running position, the lever is automatically caught and held in the off-position.

18. Three autotransformer taps are generally provided in each starter, and after a motor is installed the tap that will give best results should be selected. The taps are generally so placed that one will give from 40 to 50 per cent. of line voltage on the motor, another from 60 to 65 per cent., and the third about 80 per cent. The lowest voltage will answer where the motor starts freely; the middle tap serves in the great majority of cases, while the highest starting voltage is useful only when the motor must start with high torque, as in starting a long line shaft or a machine with heavy rotating parts.

The motor should start its load promptly and accelerate to full speed in not more than 1 minute after the switch is closed in the starting position. If a tap giving too low starting voltage is selected, the starting period will be too long, especially with frequent starting, and the autotransformers may be overheated. On the other hand, if the starting voltage is too high, the starting current will be higher than is necessary; the motor will start with a violent jerk and accelerate very rapidly. In any case, the switch should be left in starting position until the motor attains very nearly full speed and should then be thrown quickly to the running position; if this change is made too soon, an unnecessary rush of current is caused when the change is made, and if delayed too long the autotransformers may be overheated.

19. Autotransformer starters are usually provided with springs, latches, and magnets that automatically return the contacts to the off-position if the voltage fails while the motor is operating. The return of voltage cannot then cause an

injurious rush of current. Overload protection is also good practice; it is usually installed in the form of fuses or circuit-breakers. Fig. 9 shows a fuse in each running lead, but none in the starting leads. The starting current is of such short duration that it rarely works injury. The same fuses cannot be used to carry both starting and running current, because, if the fuses were large enough to carry the starting current they would be too large to afford protection from a continuous over-load that might injure the motor while running.

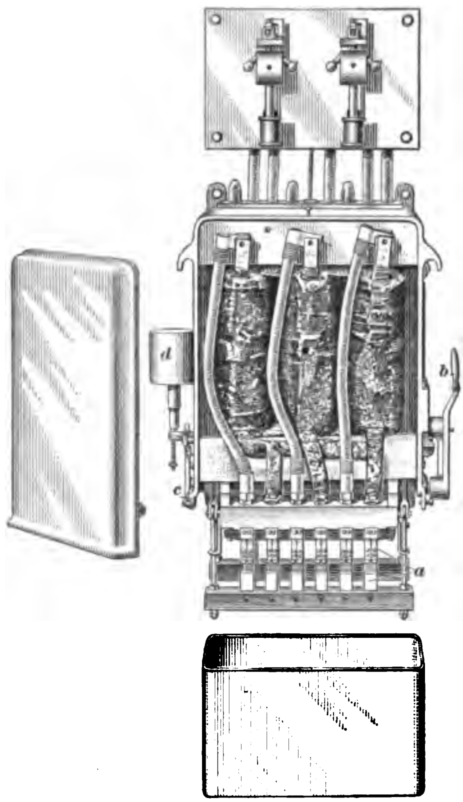
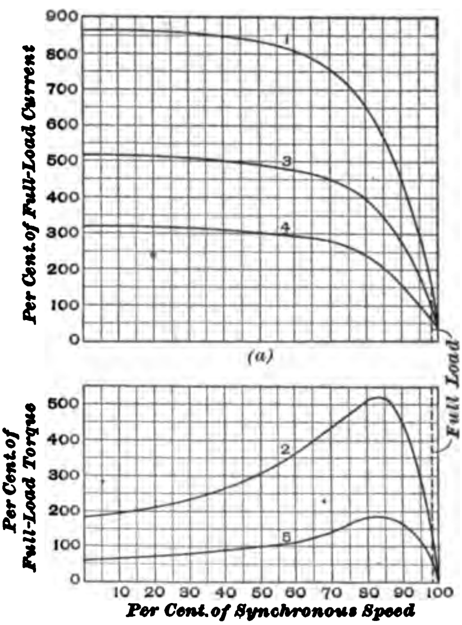


FIG. 10

Fig. 10 shows a starting compensator partly dissembled. The oil tank is lowered to show the switch contacts *a*. These are operated under oil by means of the handle *b*. The operating shaft extends through, and is connected by, levers *c* with the low-voltage device *d*, which releases a latch and allows the contacts to return to the off-position on failure of voltage while the motor is operating. Overload relays, or circuit-breakers, mounted on a panel above the compensator open and protect the motor from injury that might be caused by excessive loads. Auto-transformer starters are used with squirrel-cage induction motors of all sizes.

20. Starting Current and Torque.—Fig. 11 shows typical current and torque conditions in starting a squirrel-cage motor. Abscissas represent per cent. of synchronous speed, and ordinates represent per cent. of full-load current on curves in (*a*) and per cent. of full-load torque on curves in (*b*).

Curve *1* shows the starting current with full line voltage. At the instant the line switch is closed the current is 875 per cent. of full-load current, or nearly nine times. As the speed increases this current decreases, at first gradually and then more and more rapidly. Curve *2* shows the torque exerted by the motor when starting on full voltage; it is about 175 per cent. of full-load torque at the start, increases to more than five times full-load torque at about 85 per cent. of synchronous speed, and then falls to full load value at about 98 per cent. of synchronous speed.



(b)

FIG. 11

Curve *3* shows the motor current while starting with an autotransformer connected for 60 per cent. of line voltage in the starting position; curve *4* shows the corresponding line current, and curve *5*, the torque. The starting current in the motor is 525 per cent. of the full-load current, and the line current only 320 per cent., or approximately 60 per cent. of the motor current. The torque, curve *5*, is about 60 per cent. of full-load torque at the start, increases to nearly 200 per cent.

at 85 per cent. of synchronous speed, and falls to 100 per cent. at full-load speed. In this case, full-load speed is 98 per cent. of synchronous speed; that is, the slip is 2 per cent. The current curves do not decrease to zero at synchronous speed because of the magnetizing current, which causes the rotating field.

21. The torque of an induction motor varies as the square of the voltage impressed on the primary.

Let T = torque at full line voltage;
T_1 = torque at reduced voltage;
E = full line voltage;
E_1 = reduced voltage.

Then,
$$\frac{T_1}{T} = \frac{E_1^2}{E^2}, \text{ or } T_1 = T\frac{E_1^2}{E^2}; \quad (1)$$

also,
$$E_1 = E\sqrt{\frac{T_1}{T}} \quad (2)$$

When the full-load torque is known, the torque at any reduced voltage may be readily determined by applying formula **1**. For example, if the voltage falls from 110 normal to 100, the reduced torque is $\frac{100^2}{110^2} = \frac{100}{121} = .826$, or 82.6 per cent. of the full-load torque; in other words, a reduction of 9 per cent. in voltage reduces the torque 17.4 per cent., provided the current remains constant. If the motor load remains constant, however, the current input increases enough to give the required torque unless this torque is beyond the motor capacity, in which case the motor stops. The line voltage should therefore be kept very nearly constant, because at low voltage the motor may either stop or become overheated.

By means of formula **2** the starting voltage for any torque within the capacity of a motor can be predetermined, provided the torque of the motor at full voltage is known. For example, if a motor will start at full line voltage with 2.75 times full-load torque and only full-load torque is needed, the starting voltage should be

$$E_1 = E\sqrt{\frac{1}{2.75}} = E\sqrt{.364} = .6\ E, \text{ approximately.}$$

With a standard starter, an autotransformer tap giving 60 or 65 per cent. of full voltage for starting would be satisfactory in this case. Many induction motors are made for general service to give from 2 to 3 times full-load torque with full line voltage.

PHASE-WOUND ROTORS

22. The secondary windings of an induction motor may also consist of coils, each spanning approximately the same arc as a primary coil and all connected so that the resistance of the secondary circuit can be varied at will. The names *phase wound* and *variable resistance* apply to such secondary construction. Increasing the resistance in the secondary circuit of an induction motor reduces the starting current for a given torque; it also reduces the speed, when the motor is operating, in much the same manner as does resistance in circuit with the armature of a direct-current motor.

23. Application.—Induction motors with phase-wound secondaries are used in preference to squirrel-cage induction motors where high starting current is objectionable and where speed regulation is necessary. The high starting current taken by squirrel-cage motors disturbs the line voltage and is objectionable where: (1) motors and lights receive energy through the same circuit, (2) the feeders, or conductors, leading to the motors are small, and (3) a motor is large enough to take a considerable part of the output of the generator supplying it.

24. Under case 1, the brilliancy of the lights is decreased every time the motor starts. To avoid affecting the lights, separate circuits are frequently installed for power and lights. Under case 2, if the feeders are small, the voltage at the motor may drop considerably with high starting current and heavy overloads, and since the torque decreases with the square of the voltage, difficulty may be experienced in starting and in carrying overloads. Under case 3, high starting current will seriously affect the regulation of the generator, causing reduced voltage at the generator terminals and thus affecting the whole

system. For these reasons, many central stations insist that induction motors above a specified capacity must have phase-wound secondaries.

25. Construction.—The mechanical construction of a phase-wound secondary is essentially the same as that of a squirrel-cage secondary, but the electrical part, that is, the windings and connections, differ. The coils of the phase-wound secondary are practically always connected in three-phase star for use in both two-phase and three-phase primaries; the free end of each phase is arranged for connecting resistance in series. This resistance may be *internal* or *external* to the secondary.

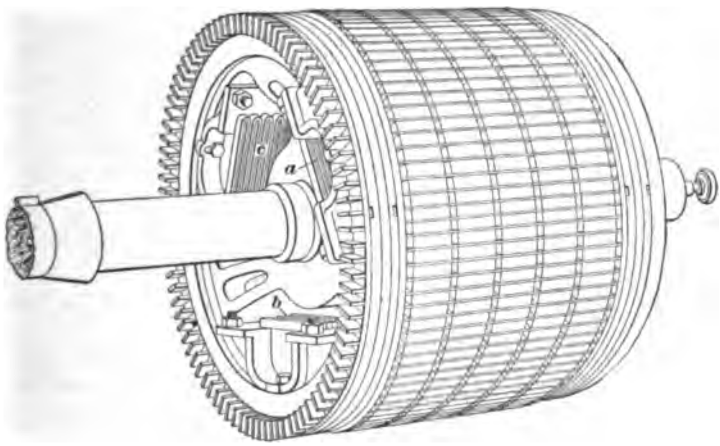


FIG. 12

26. Internal-resistance secondaries are applicable in some cases where the starting requirements are only a little too severe for squirrel-cage motors. The resistors are mounted on the rotor spider in the manner shown at *a*, *b*, and *c*, Fig. 12, and are cut in and out of the rotor circuit by moving an inside contact by means of a spindle in the center of the shaft with a knob at the outer end. This knob is shown at the extreme right; withdrawing it places the starting resistance in circuit, and pushing it in short-circuits the secondary winding. Such resistance is used for starting only, not for speed regulation.

27. Fig. 13 shows a complete induction motor of the internal-secondary-resistance type with a pulley for belt drive. In order to start the motor, the knob at the left is pulled to the outward limit of its travel and the line switch (not shown) is closed, placing full voltage on the motor primary with all resistance in the secondary circuit; after the motor has started, the knob is gradually pushed in as the speed accelerates. When the motor is up to speed and all the resistance is cut out, it operates with the same characteristics as a squirrel-cage

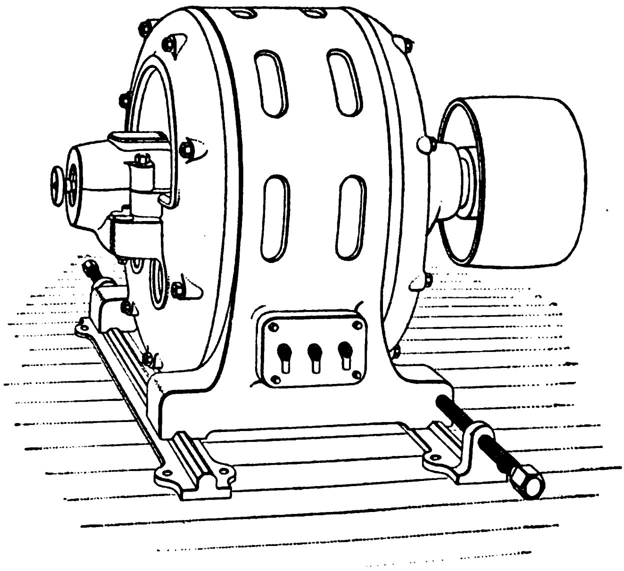


FIG. 13

motor. Applications of such internal-resistance motors are confined to constant-speed service, where low starting current is desired.

28. External-resistance secondaries are used in induction motors for starting conditions that are more severe than can be met satisfactorily with any other type of secondary and for service where speed regulation is required. The terminals of the star-connected winding are connected with collector rings on the shaft, and stationary brushes sliding on

these rings furnish a means for connecting external resistance in the secondary circuit. These *slip-ring motors*, as they are called, are much more widely used than those of the internal-resistance type.

29. Starters for slip-ring motors consist essentially of three resistors, with switching devices to adjust the connections so as to vary the amount of resistance in the secondary circuit. Fig. 14 shows typical conditions; *a*, *b*, and *c* represent the three phases of the secondary, r_1, r_2, and r_3 the three resistors, and *d* represents the switching device. This switch is indicated in the off-position, all resistance being in circuit; turning it clockwise, as indicated by the arrow, cuts the resistance out of circuit in steps. The switching device may be of the *face-plate type*, as indicated, or of the *drum type*. The drums are the same in principle as those already shown in connection with direct-current motors.

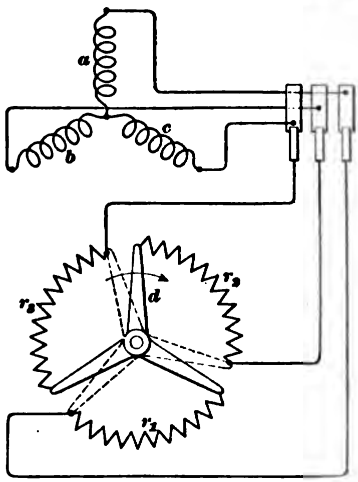
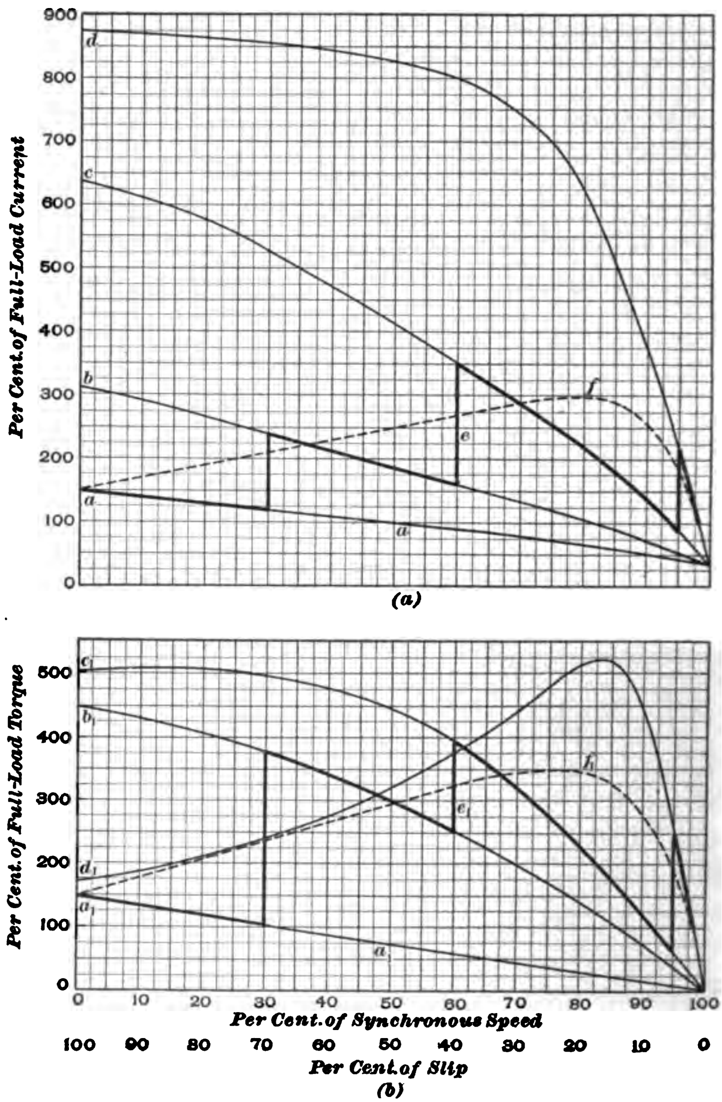


FIG. 14

30. Starting Characteristics of Phase-Wound Motors.—Fig. 15 shows the current and torque changes while starting with three sections of resistance; the curves in (*a*) show current changes and the curves in (*b*) torque changes. Curves *a* and a_1 show current and torque with all the starting resistance in circuit; curves *b* and b_1, the same conditions with one section of resistance cut out; curves *c* and c_1, with two sections out; and curves *d* and d_1, with all the starting resistance out of circuit. The heavy zigzag lines *e* and e_1 show current and torque changes as the starting resistance is cut out of circuit in steps.

According to curves *a* and a_1, the motor starts with 150 per cent. of both full-load current and full-load torque. Both



Per Cent. of Full-Load Current
900
800
700
600
500
400
300
200
100
0
d
c
b
a
a
e
f
(a)
Per Cent. of Full-Load Torque
500
400
300
200
100
0
c₁
b₁
d₁
a₁
a₁
e₁
f₁
0
10
20
30
40
50
60
70
80
90
100
Per Cent. of Synchronous Speed
100
90
80
70
60
50
40
30
20
10
0
Per Cent. of Slip
(b)

FIG. 15

decrease as the motor speed increases until the first section of resistance is cut out; when the current increases to 240 per cent., a point on curve b, and the torque to 375 per cent., a point on curve b_1. When the second and third sections of resistance are cut out, other increases of both current and torque occur, causing increased speed; in each case the values decrease as the speed increases until the motor is operating at full speed, 98 per cent. of synchronous speed (2 per cent. slip), with both current and torque at 100 per cent., or full value. If the starting resistance were cut out in very small steps, the current and torque would change more nearly as shown by the dotted curves f and f_1. The magnetizing current for the rotating field causes the current curves to end above the zero line at synchronous speed.

PERFORMANCE AND SPEED CONTROL

31. Characteristic Curves.—The curves in Fig. 16 show performance characteristics (speed, efficiency, power factor, and current) of a 100-horsepower, sixty-cycle, 440-volt, three-phase squirrel-cage induction motor. Let it be assumed that the motor is running idle; then, increasing the load causes the speed to decrease to 96.5 per cent. at full load (slip 3.5 per cent.); at the same time, the current increases to 120 amperes at full load. The efficiency reaches maximum, slightly more than 91 per cent., at 80 horsepower and remains above 90 per cent. until the load exceeds 125 horsepower. The power factor reaches 89 per cent. at full load and continues to rise until the load reaches 160 horsepower—a load greater than can be safely carried by such a motor for more than a very brief period.

32. Pull-Out Torque.—If the load of an induction motor is increased indefinitely, a point will finally be reached where the motor will *pull out* of step and stop. The torque required at this point is called the *pull-out torque*. The limit of the momentary overload capacity of the motor is reached when developing torque just below the pull-out torque. The motor for which curves are shown in Fig. 16 has a pull-out torque about two and one-half times full-load torque; after the load

has passed this point, the current increases very rapidly and all the other characteristics decrease, as shown by the sharp bends at the ends of the curves. In a line of motors for general service, the pull-out torques usually range from one and one-half to three times full-load torque. These maximum torques are of use only in starting or for very intermittent service, because they are far beyond the continuous capacities of the motors.

33. Apparent Efficiency.—The product of the efficiency and the power factor divided by 100 is the *apparent efficiency*.

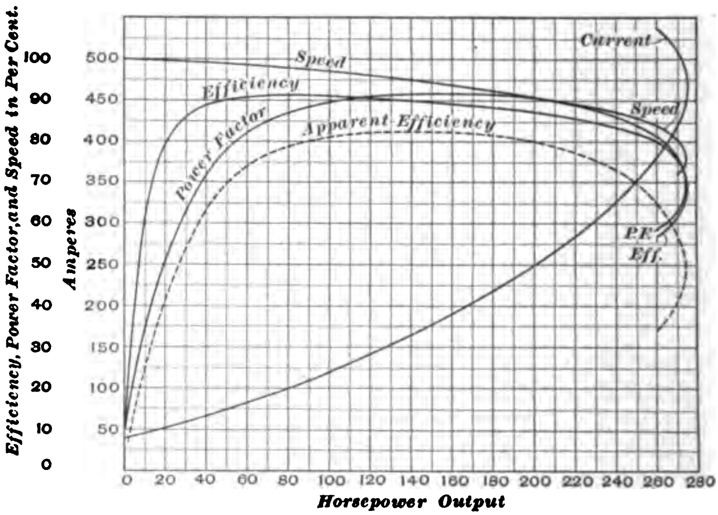


FIG. 16

For example, the full-load efficiency, as shown by the curve in Fig. 16, is 91 per cent. and the full-load power factor 89 per cent.; the apparent efficiency is $91 \times 89 \div 100 = 81$ per cent., nearly, as shown by the broken-line curve. Multiplying by 100 the ratio of the output to the apparent input also gives the apparent efficiency.

34. Speed Control by External Resistance.—Although an induction motor tends to run in synchronism with the alternator supplying it with current, it never quite reaches

synchronous speed, because some energy is necessary to overcome friction, windage, copper losses, and magnetic losses, even when the motor is running idle. Nor can the speed rise above synchronism, but, with the exception of the slight variations due to the changes in load and corresponding change in slip, the speed remains practically constant as long as the speed of the alternator and voltage on the line remain constant. Generally, the induction motor is not so well adapted for variable speed as the direct-current motor, although its speed can be varied through a considerable range. The speed of an external-resistance induction motor may be reduced by increasing the amount of resistance in the secondary circuit. When this resistance is large, the slip also must be large to induce enough current to provide the requisite torque; consequently, the greater the resistance the lower will be the speed.

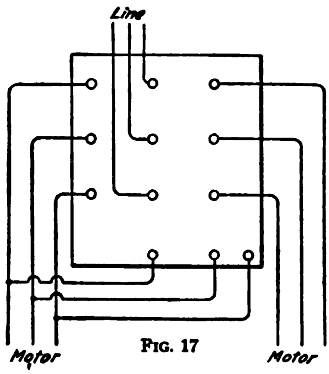


FIG. 17

The connections are the same as when starting with external resistance, Fig. 14, but the resistors and switching devices are heavier, because they must carry the secondary currents longer than for starting. This method of speed control is used for phase-wound induction motors in heavy, varying-speed service, such as on hoists and cranes.

The speed characteristics of an induction motor with control resistances in the secondary circuit are very similar to those of a direct-current motor with control resistance in the armature circuit; that is, the speed varies inversely with the load. Such motors are therefore not suitable for applications in which constant speed with varying load is required at each speed adjustment.

35. Multispeed Motors.—If only a few speed changes are required, they can be made by changing the number of primary poles. For example, six leads from a three-phase primary

can be brought to a multipoint switch, as in Fig. 17; closing this switch to the right connects the primary phases in star, and closing it to the left connects them in delta. The windings are so arranged that with star connections adjacent poles have the same polarity, as in Fig. 18 (*a*), and with delta connections adjacent poles have unlike polarity, as in (*b*). Adjacent poles N and N_1 in (*a*) combine to form one pole and S and S_1 to form another, while in (*b*) each pole remains distinct, thus giving twice as many poles in the latter case as in the former. Since the speed varies inversely as the number of poles (Art. **6**), closing the switch to the right gives double the speed obtained on closing it to the left. On a twenty-five-cycle circuit, for example, a two-pole primary gives 1,500 revolutions per minute, synchronous speed, and a four-pole primary 750 revolutions per minute.

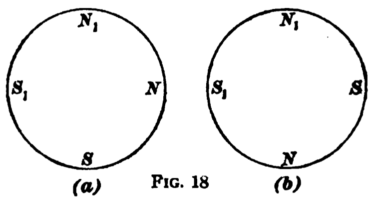


FIG. 18

Two windings can be placed on the primary similar to the one just described and arranged for connection by means of a drum-type switch to form four numbers of poles giving four speeds. The ratios in four-speed motors are usually 1, $\frac{2}{3}$, $\frac{1}{2}$, and $\frac{1}{3}$. For example, on sixty-cycle circuits, 4, 6, 8, and 12 poles give synchronous speeds of 1,800, 1,200, 900, and 600, and on twenty-five-cycle circuits the same numbers of poles give synchronous speeds of 750, 500, 375, and 250.

36. If designed for constant torque at all speeds, the horsepower of a multispeed motor varies with the speed. Even under this condition, a two-speed motor must be from 30 to 40 per cent. larger than a single-speed motor for the same torque at the highest speed, and the size of a four-speed motor must be increased from 70 to 80 per cent. If constant horsepower output is required at all speeds, a two-speed motor must be about 100 per cent. larger, and a four-speed motor about 150 per cent. larger, than a motor for the same output at the highest speed only. These figures are based on continuous operation at any of the speeds; for intermittent operation at

reduced speeds, the percentages might be different, depending on the service conditions. Increased weight and cost and complicated connections and switching arrangements are objections to multispeed motors; these objections limit their general application.

INDUCTION GENERATORS

37. If the primary of an induction motor is connected with an alternating-current circuit and the machine is driven by some external power at a speed higher than synchronism with the alternating current, the machine becomes an **induction generator** and supplies energy to the circuit; that is, this generator operates in parallel with the alternator from which it receives its magnetizing current.

Induction generators can be operated only in parallel with one or more alternators. The alternator fixes the speed above which the induction generator must be driven and furnishes the magnetizing current for the rotating field of the generator. This magnetizing current, being 90 electrical time-degrees behind the power current, reduces the power factor of the system, necessitating increased field excitation of the alternators. For example, if the power current in the primary winding of an induction generator is 100 amperes and the exciting current is 25 amperes, the total current is $\sqrt{100^2+25^2}=103.1$ amperes and the power factor of the system is $\frac{100}{103.1}=.97$, or 97 per cent., of what it would be without the induction generator.

Induction generators with squirrel-cage secondaries are the only ones in commercial use. They are of simpler construction than alternators, have no sliding contacts, and are lower in cost; but the mechanical clearance in the air gap is small and the effect on the power factor undesirable. Where induction motors are used on electric railways, this generator action, when driven above synchronism, is of some advantage for *regenerative braking* on down grades. The use of induction generators otherwise is somewhat limited, but would probably be more general if their advantages were better known.

SINGLE-PHASE MOTORS

DESCRIPTION AND CLASSIFICATION

38. The **single-phase induction motor** is essentially the same in construction as the polyphase motor, the principal difference being in the method of starting and the way in which the revolving flux is set up after the motor is running at operating speed. If an induction-motor primary is provided with only one winding and is connected with a single-phase circuit when the secondary is at rest, the magnetic poles in the primary core do not rotate, but simply reverse. Their location remains constant, and no torque tending to start a squirrel-cage rotor is developed. But if such a rotor is started in either direction, it will accelerate in that direction to a speed very nearly in synchronism with the primary current and continue to run as a single-phase induction motor.

39. The most simple explanation of these facts is that the resultant effects of the primary current and the induced current in the moving secondary establish a rotating magnetic field. At standstill, the magnetic field is stationary; as the speed increases, the flux rotation becomes more nearly like that of the polyphase motor, until at operating speed it is practically identical. A two-phase or three-phase motor will operate on one phase after it is started, but it will require considerable more energy for the same load; that is, the efficiency of a polyphase motor operating single phase is very low.

40. Small single-phase squirrel-cage motors can be started without load by pulling the belt enough to bring the speed up nearly to synchronism and applying the load after full speed is attained; the torque while accelerating is only a small part of full-load torque. This method of starting is practically never used except with very small motors and rarely even

with them; special windings are usually provided for electrical starting. Electrically, self-starting single-phase motors may be classed as *split-phase motors*, *shaded-pole motors*, *single-phase series motors*, and *repulsion motors*. In each of these classes, torque is established electrically while the motor is at a standstill.

SPLIT-PHASE MOTORS

41. In the **split-phase motor**, a form of rotating field is established for starting by using two-phase or three-phase windings and supplying these windings with displaced electromotive forces obtained by the use of resistance and inductance or resistance and capacity. Fig. 19 shows a two-phase winding with a non-inductive resistor R in series with winding A and an inductor L in series with winding B; the two windings are connected in parallel across the lines. The current in winding B is thus made to lag behind that in winding A, and if the resistance and inductance are correctly proportioned the currents can be made to differ enough in phase to produce an imperfect form of rotating field sufficient to start the motor. The windings are frequently so designed that the necessary phase displacement is caused by the windings themselves, and outside resistance and inductance are rendered unnecessary. In some cases, one of the windings is a main, or working, winding, and the other is used only at starting, its circuit being opened manually by means of a switch after the motor has attained its speed.

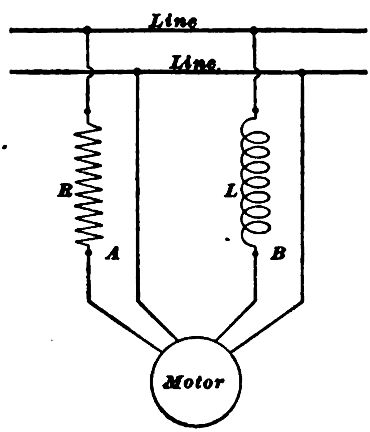


FIG. 19

Fig. 20 shows another method of starting a motor on single-phase mains. The two windings are provided with three terminals; the two outer terminals are connected to the mains,

and the middle terminal to a point *b* between the resistor *R* and the inductor *L*. The electromotive force between *a* and *b* differs in phase from that between *b* and *c*, so that the different windings of the motor are supplied with displaced electromotive forces suitable for starting. A switch is usually arranged to disconnect the resistor and the inductor automatically after the motor has come up to speed, thus placing the two primary windings in series across the single-phase circuit.

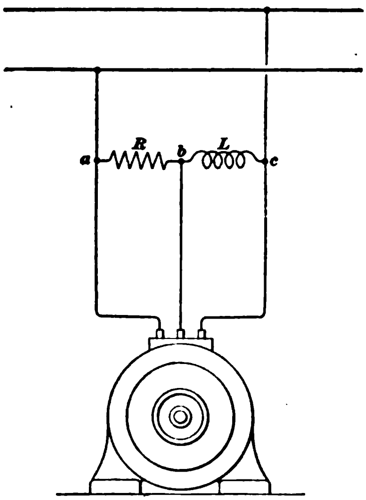


FIG. 20

Fig. 21 shows a starting arrangement similar to Fig. 20, except that a condenser *C* is used instead of the inductor *L*. With this combination, the resistor and the condenser are sometimes left in circuit after the motor has attained speed, because the condenser counteracts the self-induction of the motor and thus raises its power factor to such an extent that the small amount of loss in the resistor is more than made up.

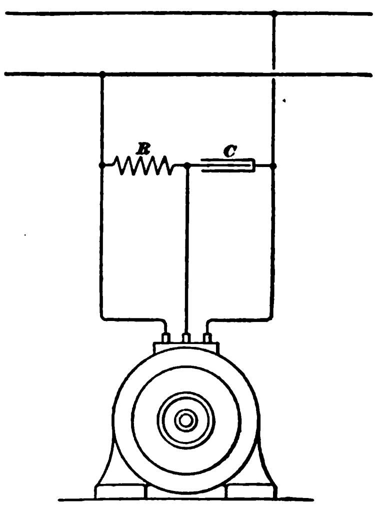


FIG. 21

SHADED-POLE MOTORS

42. Fig. 22 shows an interesting starting arrangement used to a great extent for small single-phase fan motors. Each pole piece *A*, view (*a*), is provided with a magnetizing coil *D*; in the pole piece is made a

slot *c*, in which is placed one side of a rectangular copper stamping or coil *B* called a *shading coil*. In some cases, the shading coil consists of a number of turns of wire with the two ends joined together so as to make a closed circuit. The primary coil *D* sets up a magnetic flux *a*, view (*b*), and the combined effect of coils *D* and *B* sets up a flux *b* through the part of the pole face covered by coil *B*. The flux passing through the shading coil is out of phase with that through the main coil and induces currents that are out of phase with the main flux, thus producing the effect of a shifting magnetic field to a sufficient extent to bring a small squirrel-cage rotor up to speed.

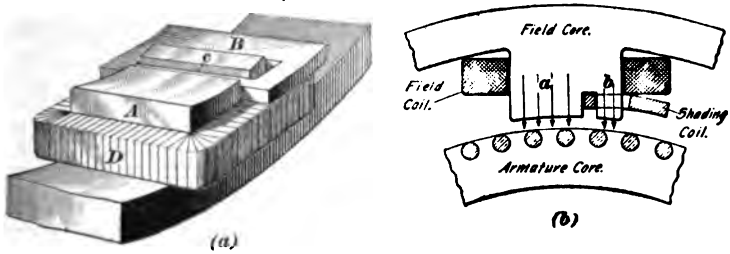


FIG. 22

SINGLE-PHASE SERIES MOTOR

43. If a series-wound direct-current motor with laminated fields is supplied with alternating current, it will start and accelerate with good torque. Since the field and the armature are in series, the current in each reverses at the same instant, and in a direct-current motor, when the currents in both field and armature are reversed simultaneously the direction of rotation remains unchanged.

The design of such motors has been so improved that they operate with little sparking. They have practically the same characteristics as the corresponding direct-current machine; the speed increases with decrease in load, and the torque is large at starting and decreases with increase in speed. The frequency on which these motors are operated must be low (twenty-five cylces or under), and as a frequency of twenty-

five has become standard in railway work, single-phase series motors have been designed chiefly for that frequency. One advantage of the motor is that it will operate on either direct or alternating current. Because of its speed characteristics, it is not adapted for industrial service in which practically constant speed is required at all loads, nor is it adapted for service in which the load may become very small at any time.

REPULSION MOTORS

44. Theory.—If the poles, Fig. 3, are excited by single-phase alternating current, alternating magnetic flux is set up through the secondary circuit and current is induced in it 90 electrical degrees behind the flux. These phase relations are shown in Fig. 23, in which curve ϕ represents the flux set up by the primary current and curve I the induced secondary

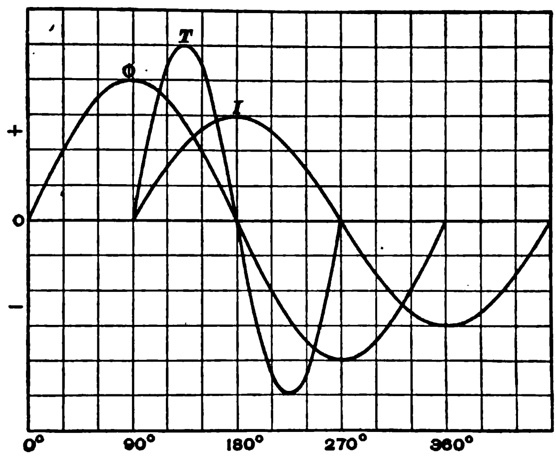


FIG. 23

current. The torque at any instant is the product of the instantaneous flux and the current; this torque is represented by the curve T, the ordinates of which are proportional to the products of the instantaneous ordinates of curves ϕ and I.

At 90 electrical degrees, ϕ is maximum positive and its rate of change is 0; I is therefore 0. Their product 0 gives one

point in the curve T. At 135 electrical degrees, the flux has decreased and the current has increased until their product gives the maximum positive point on the torque curve. At 180 electrical degrees, the flux is 0, the current maximum positive, and the torque 0. At 225 electrical degrees, the flux has become negative, the current is still positive, and the product of the two numerical values gives the maximum negative value of torque. The remainder of the curve T is derived in the same way. Between 90 and 180 electrical degrees, the torque is positive; between 180 and 270 degrees, negative;

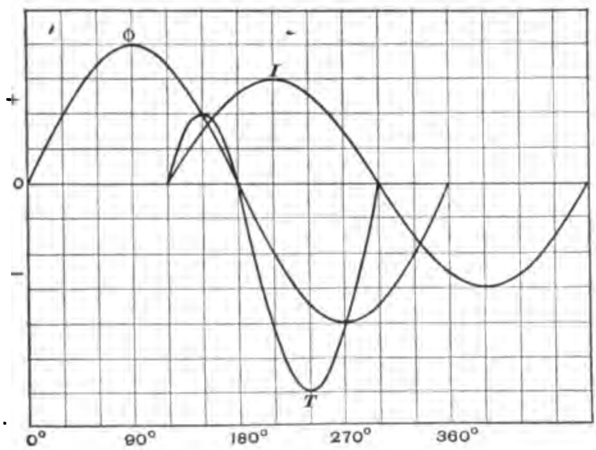


FIG. 24

between 270 and 360 degrees, positive; and so on, reversing every quarter cycle.

45. In referring again to the secondary element $a\,d\,b\,c$, Fig. 3, it will be seen that friction and inertia prevent its sudden movement in response to the reversing torque. The most this torque can do is to cause slight oscillations of the secondary. If the element could move quickly enough, it would be *repelled* during the first quarter cycle to a position in which its plane would be parallel to the direction of the lines of force. If the rotating element in Fig. 3 could move to such a position, the reversing magnetic flux could then exert no further influence

on it, and such an arrangement could not therefore produce rotary motion.

46. The conditions shown in Fig. 23 could prevail only when the secondary current is in phase with the secondary induced electromotive force; that is, when the secondary circuit has no self-induction. Fig. 24 shows more common conditions; here, the secondary current lags behind the secondary electromotive force, or is more than 90 electrical degrees from the primary flux ϕ. The torque curve T is derived, as before, by making its ordinates proportional to the products of the ordinates of the flux and current curves. In this case the

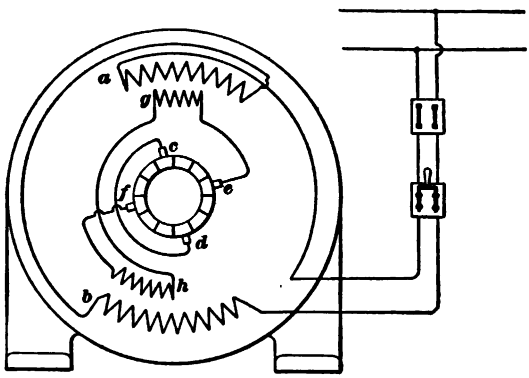


Fig. 25

larger part of the torque is negative, as shown by the negative loop of the torque curve being larger than the positive loop. The positive loop may be considered an attractive force, and the negative loop a repelling force.

47. Commuted Winding.—By arranging the conducting elements of the secondary so that they are closed, or short-circuited, only when in position to take advantage of this repelling force, the secondary will rotate, forming a *repulsion motor*. This arrangement is effected by winding the secondary with coils and connecting them with the segments of a commutator, essentially the same as for a direct-current motor. Interconnected brushes in contact with the proper points on the

commutator short-circuit secondary coils when in position to be affected by the repelling force, leaving the coils in other positions open-circuited.

48. Fig. 25 indicates the windings of a single-phase repulsion motor, with primary windings *a* and *b* connected with a single-phase circuit through a switch and fuses. The short-circuiting brushes *c* and *d* are called *energy brushes* because through them is established the current that produces the torque. Two additional brushes *e* and *f*, displaced approxi-

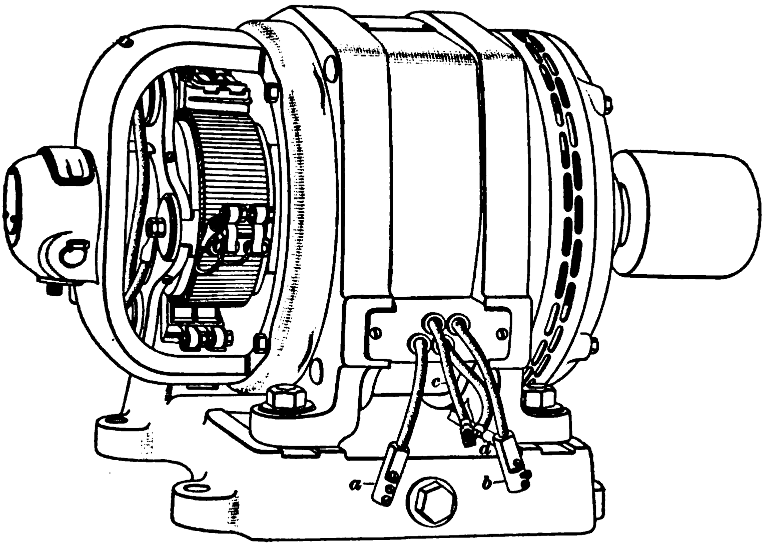


FIG. 26

mately 90 electrical space-degrees from the energy brushes, are connected with a winding *g h* on the primary. This winding acts as the secondary of a transformer, receiving its energy from the primary windings *a* and *b*. Current in the circuit of winding *g h* serves to maintain the power factor at nearly unity and to make the speed of the motor stable; this winding is therefore called *compensating*, and brushes *e* and *f* are the *compensating brushes*.

49. The speed of such motors can be regulated by changing the resistance of energy and compensating circuits. Increasing

the resistance in the energy circuit or decreasing the resistance in the compensating circuit reduces the speed, and vice versa. For speed regulation, the two circuits are closed through a controller having independent resistances for each circuit; a movement of the controller handle simultaneously changes the resistance in both circuits, thereby decreasing or increasing the speed, according to which way the handle is moved. Standard controllers for this purpose give a range of speed from 40 per cent. below to 10 per cent. above normal, provided the motor is operating with full-load torque for all speeds; the output varies directly with the speed.

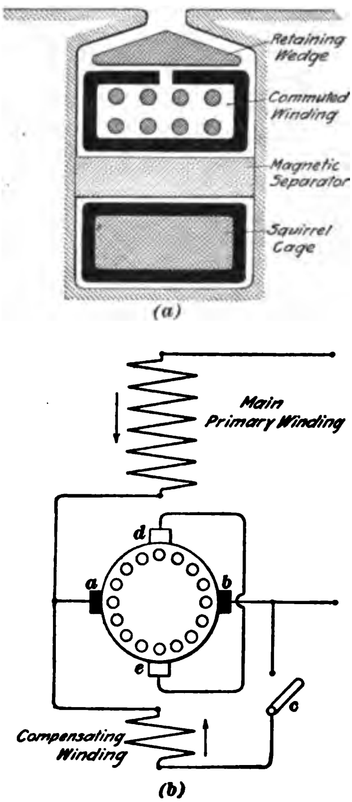


FIG. 27

50. Fig. 26 shows a typical single-phase repulsion induction motor with four primary terminal leads *a*, *b*, *c*, and *d* brought out from two main primary windings. These leads are shown joined for connection with a 220-volt circuit, the connections being made with terminals *a* and *b*; by joining lead *c* to lead *a* and lead *d* to lead *b* the motor can be operated from a 110-volt circuit. Two of the sets of brushes shown on the commutator are energy brushes and the other two compensating brushes. Such motors are made only in sizes up to about 10 horsepower; they compare favorably with polyphase induction motors of corresponding ratings in starting torque, maximum overload capacity, efficiency, and power factor.

51. In one of the most successful single-phase repulsion induction motors the secondary has two windings, a commuted winding and a squirrel-cage winding, between which each slot contains a magnetic separator, as shown in Fig. 27 (*a*). The connections are shown in (*b*). In starting, the main primary winding is connected through the compensating brushes *a* and *b*, while the circuit of the compensating winding is open at the switch *c*. The magnetic separator gives the squirrel-cage conductors high inductance at the high frequency while starting, thus preventing current from building up in them until the rotor approaches synchronous speed, at which speed the secondary frequency is lower.

Most of the starting torque is therefore developed by the current in the commuted winding and in the circuit of the energy brushes *d* and *e*, as in a repulsion motor. As the speed increases, however, the secondary frequency decreases and the induced current in the squirrel-cage winding increases, until the motor operates nearly the same as a squirrel-cage motor. At a speed near synchronism the switch *c* closes automatically, after which the effects of the commuted winding and the compensating winding combine to keep the power factor nearly at unity.

SYNCHRONOUS MOTORS

52. Synchronous motors are made to operate on either single-phase or polyphase systems, and are so called because they always run in synchronism with the alternator that drives them. In construction they are almost identical with alternators, and they always consist of the two essential parts, field and armature, either of which may rotate. The field, which is usually the rotating part, must be excited from a separate continuous-current machine in the same way as an alternator; collector rings are therefore needed to carry the exciting current to the rotating field, as on an alternator. In fact, either an alternator or a synchronous motor can be made to serve the purpose of the other, although when designed for motor service the rotating field is generally provided with a

squirrel-cage starting winding, as shown by the partial construction in Fig. 28. Uninsulated bars in slots in the pole

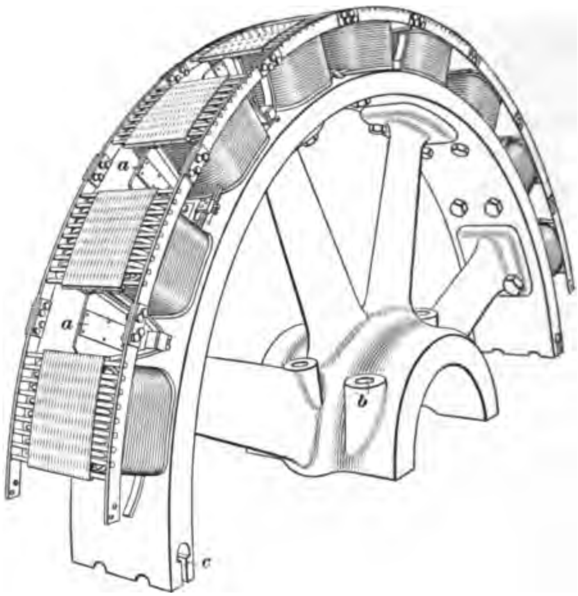


Fig. 28

faces are fastened to short-circuiting rings at the ends. The vanes *a* between the poles are to prevent air-currents from passing between the poles instead of through ducts in the armature. The holes *b* and the slots *c* are for bolting and keying the two halves of the hub and the rim.

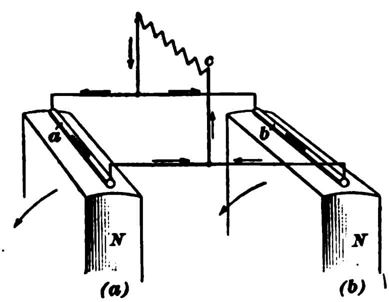


Fig. 29

53. Theory.—Fig. 29 indicates similar elements of two alternators, *N* representing north poles, one on each machine, and *a* and *b* conductors occupying similar positions on the two machines. The poles *N* are assumed to be rotating in the direction indicated by the curved arrows. At

the instant indicated, the voltages generated in the two conductors *a* and *b* are exactly opposed to each other in the circuit connecting them, or 180 time-degrees apart, as indicated by the small arrows. These two voltages unite, however, to cause current in an external circuit *c*. If the speeds and field strengths of the two machines are properly adjusted, no interchange of current will occur between them, but the currents from the two will unite to form the current in the external circuit. This is the ideal condition for parallel operation of two alternators.

If either alternator, say (*b*), is disconnected from the source of mechanical power driving it, this machine will cease to furnish current to the external circuit, but will continue to run

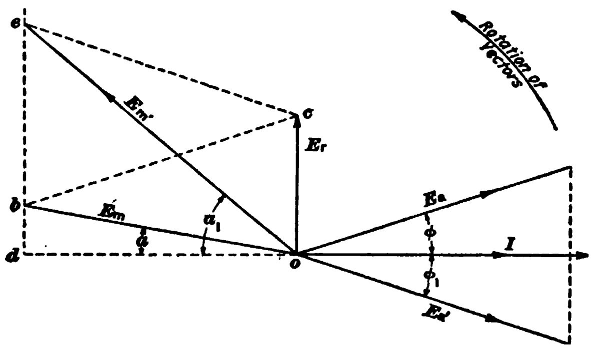


Fig. 30

as a motor, taking current from the other machine *a* in proportion to the motor losses and the motor load. Machine (*a*) continues to operate as an alternator and delivers current to operate machine (*b*). The motor (*b*) does not remain in exact phase opposition to the alternator; the voltage in conductor *b* is now behind that in conductor *a* 180°+ an angle proportional to the motor load. If the load is increased, this angle increases until the load becomes so great that the motor pulls out of step and stops.

54. The machine operating as a motor therefore generates voltage nearly opposed, or counter, to that of the generator; the resultant of these two voltages causes the current through the two machines. Fig. 30 shows the conditions. Vector E_a

represents the alternator voltage; E_m, the motor voltage, a little more than 180 time-degrees behind E_a; and E_r, their resultant, which causes the current represented by vector I. This current is assumed to be lagging behind the alternator voltage by an angle ϕ. The resultant E_r is found in the usual way by drawing from the extremity of E_m a line $b\,c$ equal and parallel to E_a and connecting the origin o with the extremity c of this line.

55. Change of Field Excitation.—If the field current of a synchronous motor operating with lagging line current is gradually increased while the load remains constant, the line current at first decreases to a minimum value and then increases again. The motor speed cannot change, for it must remain in synchronism with the alternator; nor does the line voltage change. The motor voltage, however, must change with change of field excitation.

Assume, for example, that with the conditions shown in Fig. 30, the motor field excitation is increased indefinitely; the line current I will first become minimum and then increase again to its original value. The resultant voltage E_r causing this current must then be the same as before. The line voltage has not changed, nor has the power taken from the line, but the phase relation of the line current and the line voltage has changed from an angle of lead ϕ to an angle of lag ϕ_1 such that $I\,E_a \cos\phi = I\,E_a' \cos\phi_1$. As E_a and E_a' are the same in value, simply having changed in phase relation with the line current, $\cos\phi = \cos\phi_1$, or $\phi = \phi_1$.

Increasing the motor field excitation must have increased the motor voltage from E_m to some value E_m'. As the motor load is constant, $I\,E_m \cos a = I\,E_m' \cos a_1$, or $E_m \cos a = E_m' \cos a_1 = o\,d$, in which $\cos a$ and $\cos a_1$ are the components of the motor voltages in direct opposition to the line current. The extremities of vectors E_m and E_m' must then be on a line $d\,e$ perpendicular to the direction of the current vector. As E_r is the vectorial sum of E_a' and E_m', the latter vector is fixed by drawing a line $c\,e$ parallel to E_a' and equal to it in length, fixing the point e on the vertical $d\,e$.

Fig. 30 shows that increasing the field excitation of a synchronous motor changes the phase relation of the line voltage from lead to lag, or, as this change is usually expressed, a lagging line current is changed to a leading line current. Between the two conditions assumed for this illustration is a field excitation at which the line current and the line voltage are in phase;

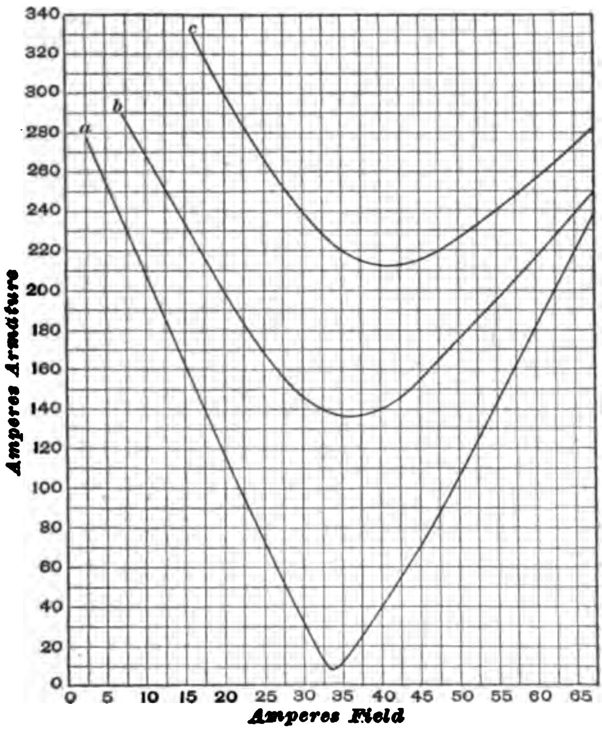


FIG. 31

that is, the power factor is unity. At this point the line current is minimum, a desirable condition in alternating-current circuits.

56. Characteristic Curves.—Fig. 31 shows the change of line current caused by changing the excitation of a three-phase synchronous motor with three constant-load conditions; this motor is wound for sixty cycles, 2,300 volts, 840 kilovolt-amperes, and 720 revolutions per minute. Curve *a* shows the

effect with no load; as the field amperes are increased, the line current decreases to the minimum of 8 amperes per phase at a field current of about 34 amperes. This minimum line current indicates that the line voltage and the line current are in phase; the angle of the phase difference between voltage and current is therefore 0, and the power factor is unity. The entire power input to the motor is then required for the motor losses and it can be found by the formula for three-phase power; thus,

$$\frac{\sqrt{3}\,I\,E\cos\phi}{1{,}000}=\frac{\sqrt{3}\times 8\times 2{,}300\times 1}{1{,}000}=32 \text{ kilowatts.}$$

With the load represented by curve *b*, the minimum line current is 136 amperes, occurring when the field current is 36 amperes. The input is then $\frac{\sqrt{3}\times 136\times 2{,}300\times 1}{1{,}000}=542$ kilowatts. The losses are now considerably greater than at no load; if they are assumed to be 42 kilowatts, the output in mechanical power is 500 kilowatts. Curve *c* represents another load condition with a minimum line current of 212 amperes, occurring when the field current is 41 amperes. The power input to the motor is then $\frac{\sqrt{3}\times 212\times 2{,}300\times 1}{1{,}000}=845$ kilowatts, and if the loss is assumed to be 45 kilowatts the output is 800 kilowatts. At each of these three loads the input is the same at all line currents; the change in line current corresponds to the change of power factor $\cos\phi$ caused by the change of field excitation.

57. With any load condition, the power factor can be adjusted to any value between wide limits, as shown in Fig. 31, by adjusting the field current. Increasing or decreasing the field excitation for the point at which minimum armature current is obtained decreases the power factor; increased excitation gives leading line current, and decreased excitation gives lagging current. The power at any power factor can be measured by wattmeters, but to avoid errors when making tests, the field current is customarily adjusted for minimum armature current and the wattmeter readings are then checked by comparing them with the power computed from the voltmeter and ammeter readings.

58. Synchronous Condensers.—The effect of a condenser in an alternating-current circuit is to cause leading current, as explained in *Alternating Currents*, Part 1. Since a synchronous motor with overexcited fields has the same effect, the name *synchronous condenser* or *rotary condenser* is often applied to a motor operated for this purpose. Distribution systems loaded with induction motors and transformers have low power factors that cause lagging current, which can be corrected by the use of synchronous condensers. When the limit of generating and distributing ability in such a system has been reached, the installation of one or more synchronous condensers will raise the power factor and thus make possible the delivery of more energy with the same current by reducing the idle, or wattless, current.

This effect may be produced by overexciting the fields of a synchronous motor used to drive a pump, a compressor, or some other steady load, thus making the motor output partly electrical and partly mechanical; or, an idle alternator may be allowed to run as a motor with overexcited field. If a water-wheel-driven alternator is so used, the water can be entirely shut off; but if the alternator is steam-turbine-driven, about the same amount of steam should be admitted to the turbine as would be required to run the set at full speed without load. Without this steam, the turbine buckets might overheat, owing to excessive windage. A machine designed purposely for a synchronous condenser usually has a very small air gap, or clearance, between the stator and the rotor in order that maximum overexcitation may be obtained.

59. Selection of a Synchronous Condenser.—If a machine is selected to operate as a synchronous condenser only, its capacity should be determined according to the power used in the circuit and the power factor. For example, the capacity of a synchronous condenser to run without motor load and raise the power factor from 65 per cent. to 90 per cent. in a circuit carrying a total load of 450 kilowatts can be calculated as illustrated in Fig. 32. The results of the calculations are in most cases here given approximately correct.

The power component, 450 kilowatts, divided by the power factor .65 gives the kilovolt-amperes 690; the wattless component is $\sqrt{690^2-450^2}=525$ kilovolt-amperes. With the power factor 90 per cent., the apparent load is $450\div.9=500$ kilovolt-amperes, and the wattless component $\sqrt{500^2-450^2}=220$ kilovolt-amperes. The condenser must supply the difference between these two wattless components, or $525-220=305$ kilovolt-amperes, at 0 power factor.

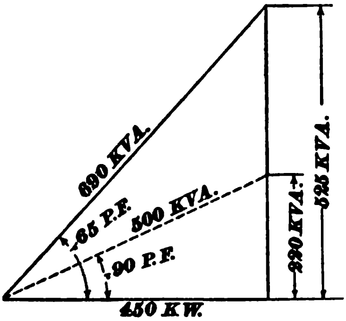


FIG. 32

60. If the synchronous machine is to operate as both a motor and a synchronous condenser, its capacity must be equal to both requirements. Assuming the same load and power factor conditions as in Fig. 32, but with an additional motor load of 150 kilowatts, the problem can be solved as illustrated in Fig. 33, the results of calculations being given in round numbers, as before.

The total power component is now $450+150=600$ kilowatts. With the power component 450 kilowatts and power factor 65 per cent., the corresponding apparent load is 690 kilovolt-amperes and the wattless component 525 kilovolt-amperes, as before. With the power component 600 kilowatts and the power factor 90 per cent., the apparent load is $600\div.9=667$ kilovolt-amperes and the wattless component $\sqrt{667^2-600^2}=290$ kilovolt-amperes. The condenser must then supply a wattless component of $525-290=235$ kilovolt-amperes in addition to its power component of 150 kilowatts. Its rating must therefore be $\sqrt{150^2+235^2}$

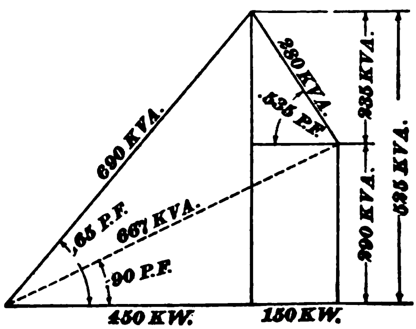


FIG. 33

$=280$ kilovolt-amperes and its power factor $150 \div 280 = .535$, or 53.5 per cent.

61. Starting Synchronous Motors and Condensers. The very high starting current required by the earlier types of synchronous motors was objectionable on account of disturbance of the line voltage. Small induction motors were generally used for starting, but they were disconnected from the synchronous motors after the latter were up to speed and connected with the line. The later types of synchronous motors have squirrel-cage windings over the pole faces (Art. 52) and start readily as induction motors, with considerable torque on reduced voltage from autotransformers. The speed can thus be brought to a point from which the motor will pull into synchronism when switched on to the circuit.

62. In order that the rush of current shall not be excessive when the line switch is closed, the slip as an induction motor must not be large; but, on the other hand, the resistance of the squirrel-cage winding must be enough to give good starting torque. The ideal condition would be with a squirrel-cage winding of high resistance at start and with decreasing resistance as the speed increases. This condition can be approached by taking advantage of the resistance caused by skin effect, or eddy currents, in the conductors of the starting winding.

At start, the frequency of the current induced in the starting winding is the same as that of the primary current; as the speed increases, the frequency of the secondary current decreases until at synchronism it is zero. As the skin effect varies with the frequency, it is greatest at start and decreases as the speed increases. By proportioning the bars of the squirrel-cage winding so that the skin effect will be large, the effective resistance can thus be made to vary so as to obtain high starting torque and comparatively low slip.

63. Insulation of Field Windings.—The field windings of synchronous motors must be specially well insulated, because very high electromotive forces may be induced in them while

starting. During the starting period, both the squirrel-cage winding and the field coils act as secondaries, the flux through them reversing at a frequency that corresponds to the primary frequency at first and decreasing as the speed increases.

64. Applications.—Synchronous motors are best adapted to loads that are fairly continuous and steady. Frequent starting should be avoided, and fluctuating loads are not generally desirable. Ideal applications are pumps, compressors, blowers, and fans that operate for long periods without stopping and with little change of load. Provision must usually be made to start such motors with only a fraction, usually less than one-third of full-load torque.

SYNCHRONOUS CONVERTERS

CONSTRUCTION

65. A **synchronous converter** is a machine for changing alternating current to direct current or direct current to alternating current; *rotary transformer* and *rotary converter* are older names for the same machine. Synchronous converters are largely used in connection with electric-railway work to convert the alternating current with which electric energy is economically transmitted to direct current for operating the car motors. A similar conversion is necessary at many electrolytic and electroplating plants.

66. In its essential features and general appearance, a synchronous converter is much like a direct-current generator; it has also some features of construction and some operating characteristics in common with a synchronous motor having a rotating armature. Fig. 34 shows the general appearance of a typical three-phase rotary converter. The armature has only one winding in the form of a closed drum; at one end the armature conductors are connected with segments of a commutator, and at the other end are collector rings connected with some of the commutator segments.

When the armature rotates in the magnetic field, alternating electromotive forces are induced in the armature conductors. Through the commutator, these electromotive forces may be used to establish direct current in an external circuit, and through the collector rings the same forces may be used to establish alternating current in another circuit. In fact, alternating current can be taken from one end and direct cur-

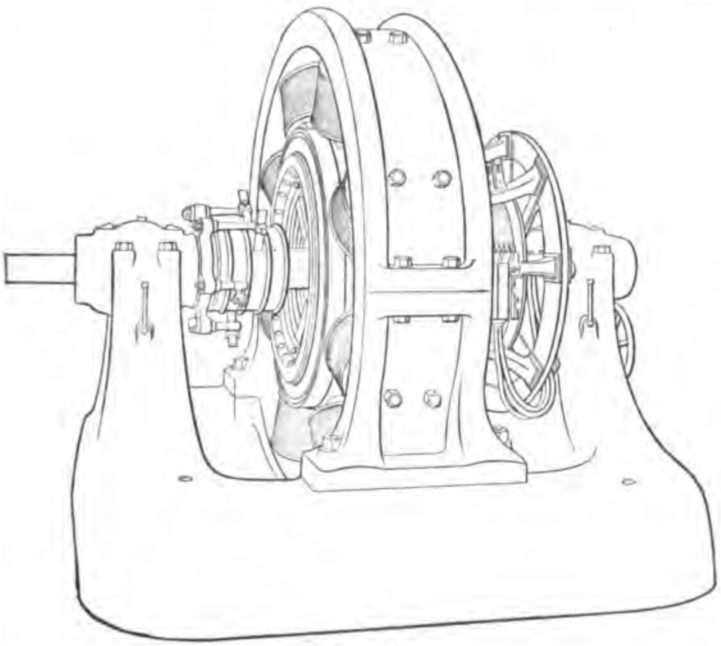


Fig. 34

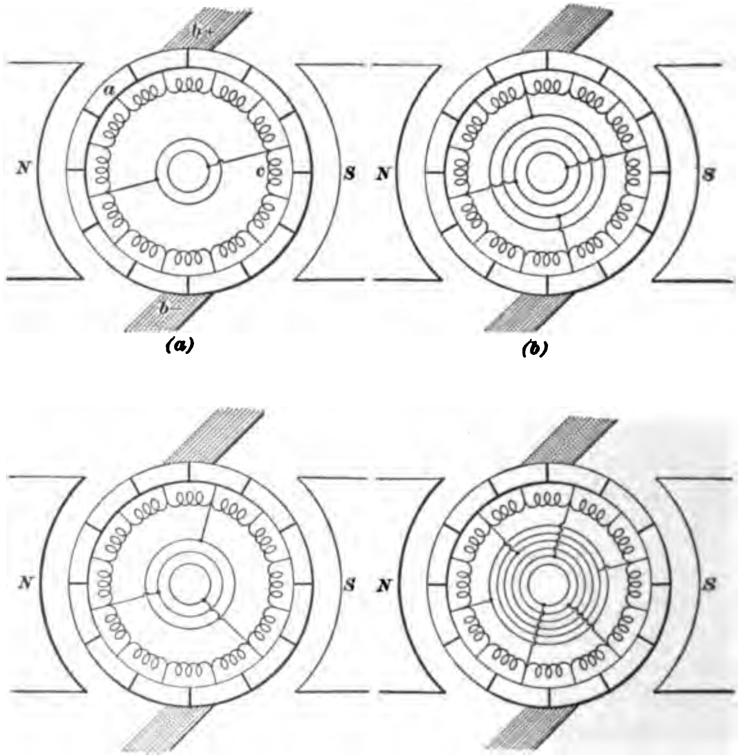
rent from the other at the same time. Suitable current supplied to either the commutator or the rings will cause the machine to run as a motor and in so doing act as a generator delivering current from the other end.

67. As generally used, synchronous converters are supplied with alternating-current energy and operate as synchronous motors, while direct-current energy is delivered from the commutator end. When the machine is run as a direct-current

motor to deliver alternating current, it is generally called an *inverted synchronous converter;* when run by mechanical power and made to deliver both kinds of current, it is called a *double-current generator.*

INTERNAL CONNECTIONS AND VOLTAGE RATIOS

68. Fig. 35 shows connections of armatures for bipolar synchronous converters. The segments *a* represent the bars of the commutator, on which rest the bushes $b+$ and $b-$.



(a) (b) (c) (d)

FIG. 35

The armature coils *c* are represented for convenience inside the commutator, though it must be remembered that these coils are in slots on a drum; also, that the ends of the coils

are connected with the commutator bars, as shown, and that extra leads extend from some of the bars through the slots and to collector rings on the shaft at the end of the armature opposite the commutator. These rings also are represented inside the commutator. To make the connections more simple, only twelve commutator bars are represented, though in practice many more bars and armature coils are used. With the brushes in the positions shown relative to the poles, the following relations between the alternating-current and the direct-current voltages exist:

69. Fig. 35 (*a*) shows the connections for a **single-phase converter;** diametrically opposite bars are connected with the collector rings. The electromotive force between these rings is maximum when the bars with which they are connected are directly under the brushes and minimum, or zero, when these bars are midway between the brushes. The electromotive force between the rings is therefore alternating, with its maximum value equal to the direct-current voltage. As the effective value of a sine-wave alternating electromotive force is .707 times its maximum value, the effective voltage E_{a1} between the collector rings is .707 times the direct voltage E_d across the brushes; or, in single-phase converters,

$$E_{a1} = .707\ E_d$$

70. Fig. 35 (*b*) shows **two-phase,** or **quarter-phase, connections** with four rings connected with four bars spaced equally around the commutator. Each pair of rings belonging to a phase is connected with bars diametrically opposite each other, as in single-phase connections, and the voltage between either pair of rings in a two-phase converter is

$$E_{a2} = .707\ E_d$$

71. In **three-phase connections,** Fig. 35 (*c*), three bars spaced equidistant from one another are connected with three rings. The maximum voltage between any two collector rings can be proved geometrically to be .866 times the direct-current voltage, and since the effective voltage is .707 times the maximum voltage,

$$E_{a3} = .707 \times .866\ E_d = .612 E_d$$

72. Six-phase connections are made by joining six collector rings with six bars at equidistant points on the commutator, as in Fig. 35 (*d*). The external connections are made by providing each secondary coil of the three-phase transformer supplying current with two leads and connecting each pair of leads with a pair of rings. The rings of each pair so formed must be connected with commutator bars either diametrically opposite each other, or 120 electrical degrees apart; the former connections are known as *six-phase diametrical* and the latter as *six-phase double delta*. With six-phase diametrical connection, the voltage per phase bears the same relation to the direct voltage as in a single-phase converter; and with six-phase double-delta connection, the relation is the same as in a three-phase converter, or

$$E_{a6} \text{ (diametrical)} = .707\ E_d$$
$$E_{a6} \text{ (double delta)} = .612\ E_d$$

73. Multipolar Connections.—The connections between the collector rings and the commutator bars in multipolar synchronous converters may be the same as shown in Fig. 35, provided the armature is series-wound, or wave-wound. If parallel-wound, or lap-wound, each collector ring must be connected with one bar for each pair of poles, and the bars with which each ring is connected must be 360 electrical space-degrees apart. For example, in a four-pole rotary with a parallel-wound armature, each ring must be connected with two bars 360 electrical space-degrees, or 180 mechanical space-degrees apart. The electrical space-degrees between bars with which the rings of each phase are connected are in all cases the same as shown in Fig. 35, namely, 180 for diametrical connections and 120 for three-phase and six-phase double-delta connections.

OPERATING CHARACTERISTICS

74. Alternating-Current Operation.—When operating in the usual way, with alternating current, a synchronous converter has practically the same operating characteristics as a synchronous motor; it runs in synchronism with the supply current and changing the field excitation does not affect the

speed. Such a change does, however, affect the power factor, and to some extent the ratio of the alternating voltage to the direct voltage. Synchronous converters, if specially designed for the purpose, can therefore be used to improve the power factor.

75. Direct-Current Operation.—When operating as an inverted synchronous converter, the characteristics resemble those of a shunt-wound direct-current motor. Weakening the field increases the speed, and this result sometimes follows the demagnetizing effect of lagging current in the alternating-current circuit. If the latter circuit is short-circuited, the heavy alternating current may so weaken the field as to cause excessive speed.

Moreover, when a compound-wound converter is operating in the usual way in parallel with other converters or with storage batteries, the opening of the alternating-current circuit-breaker causes the converter to operate as a direct-current motor with the direction of current reversed in the armature and series field; as the series field then opposes the shunt field, a weakened field and high speed results. Machines intended for operation as inverted synchronous converters should therefore be shunt-wound.

All synchronous converters are liable through accident to attain dangerous speeds by power supplied through the direct-current end. To guard against this, every synchronous converter is equipped with a device that automatically opens the direct-current circuit when the speed exceeds a given limit. There is also a slight chance that the alternating-current source of energy may, by accident, attain a high speed. For instance, waterwheel-driven alternators may run at nearly double speed due to failure of the waterwheel governor. In such cases, all synchronous apparatus on the line operates at correspondingly increased speed. Synchronous converters are designed to stand double normal speed, and safety devices on the alternating-current side are therefore unnecessary. A device is also commonly provided to oscillate the armature endwise enough to produce even wear of the commutator by the brushes.

76. Starting.—Synchronous converters can be started: (1) by means of induction motors direct-connected to the converter shafts; (2) as direct-current motors where such current is available, or (3) as alternating-current motors. The last method is most common. A modified type of squirrel-cage winding is embedded in the pole faces, giving induction-motor characteristics in starting. A *field break-up switch* opens the field circuit in several places to prevent the induction of excessively high voltages in the field windings by the alternating flux in the poles while starting. Methods of starting and synchronizing converters are fully discussed in another Section.

TABLE I

COMPARISON OF A GENERATOR AND A SYNCHRONOUS CONVERTER AT 100 PER CENT. POWER FACTOR

Function of Machine	Heating Effect of Given Current Per Cent.	Current Capacity for Given Heating Effect Per Cent.
Direct-current generator...	100	100
Single-phase converter.....	147	82
Two-phase converter	39	161
Three-phase converter.....	59	131
Six-phase converter	27	194

77. Heating Effect.—With any given current output, the heating effect in the armature of a polyphase synchronous converter is less than it would be if the same machine were mechanically driven as a generator with the same current output. The current in the armature bars is approximately equal to the difference between the direct and the alternating current, and, therefore, its heating effect is less than that of direct current for the corresponding output.

The heating of conductors nearest the tapping points is the greatest. Increasing the number of tapping points produces a more uniform heating of the armature conductors and allows a greater output. This is the reason for the increase in capacity

with an increase in the number of phases. The relative heating effects and the relative carrying capacities for a given heating effect are as recorded in Table I. These comparative figures are for a given machine used as a generator or as a converter and are true only when the alternating current and electromotive force are in phase; if out of phase, the heating effect in the synchronous converter is increased and the relative current capacity correspondingly decreased.

78. In a single-phase converter, the coils near the tapping points carry more current than they would if the machine were mechanically driven as a direct-current generator, making the heating effect greater and the carrying capacity for a given heating effect less. In a polyphase converter, the current is less in all coils than it would be if the same machine were used as a generator with the same direct-current output, resulting in decreased relative heating effect. Polyphase converters are therefore made smaller than direct-current generators for the same outputs. For example, a six-phase synchronous converter need be only about one-half as large as a direct-current generator for the same output with the same heating.

79. Commutation.—The commutation in a synchronous converter is better than that in a non-commutating-pole generator with the same direct-current output, because the effects of direct current and alternating current neutralize each other to some extent in the converter armature. Considerably larger currents can therefore be commutated successfully by a converter than by the corresponding direct-current generator. However, because of decreased heating effect in synchronous converters, commutation rather than heating formerly limited their output. Especially was this true in railway work, in which the load is subject to wide variation. The machines were therefore larger than necessary for cool running, because of liability to sparking and flashing at the commutator with the excessive currents occasionally required.

80. Commutating-Pole Synchronous Converters. Commutating poles have so increased the commutation limit of all direct-current dynamos that synchronous converters

with such poles are made much smaller for a given output than was possible with non-commutating-pole converters. The newer machines are very serviceable in all synchronous-converter work, and especially so in high-voltage direct-current systems. In some cases, excessive momentary overloads up to more than three times the normal rated capacity of the machine are made possible by the commutating poles. In starting such machines with alternating current, however, excessive sparking occurs at the commutator if the brushes remain in contact during the starting period. Converters for starting by this method are therefore provided with devices for lifting the brushes from the commutator while starting.

REGULATION OF DIRECT-CURRENT VOLTAGE

81. When a synchronous converter operates on alternating current, the direct-current voltage can be regulated by means of any of the following devices and methods: (1) By an

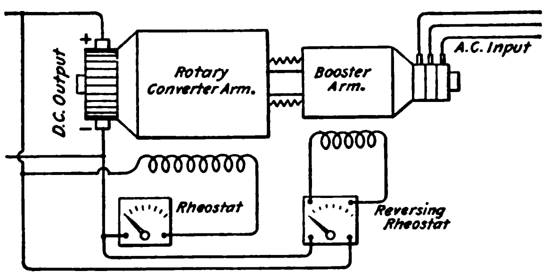


Fig. 36

alternating-current synchronous booster; (2) by a regulating-pole synchronous converter; (3) by an induction regulator or a regulating transformer; (4) by a direct-current booster; and (5) by adjustment of field excitation.

82. Synchronous Booster Converter.—A **synchronous booster** is an alternating-current generator with its rotating member, which may be either armature or field, mounted on the same shaft as the armature of the synchronous converter. The field of the generator has the same number of

poles as the synchronous converter and is excited by current from the direct-current end of the converter, as shown in Fig. 36; the excitation can be adjusted manually or automatically in either direction. Alternating current enters the booster, and the voltage is raised or depressed, as required, in the booster armature, thus regulating the direct-current voltage. The booster and the converter are compactly assembled as a unit, as shown in Fig. 37; current from the booster armature passes directly into the converter armature.

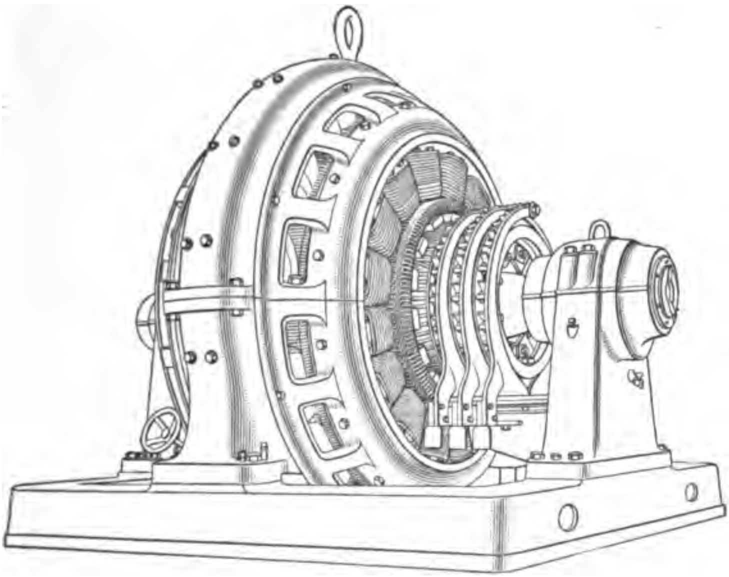


FIG. 37

Any necessary range of voltage can be provided for in the design of the booster and the converter, though 15 per cent. each way from normal voltage is usually sufficient. Automatic adjustment can be provided, so that the converter will carry its proper share of the load when operating in parallel with other converters or with storage batteries.

83. Regulating-Pole Converter.—The fixed relations between alternating and direct voltages in a rotary converter, as given in Arts. 69 to 72, inclusive, exist only when the direct-

current brushes are so placed that the direct voltage equals the maximum alternating voltage when the collector rings are connected diametrically, as in Fig. 35 (*a*) and (*b*) and .866 times this value with the three-phase connection, Fig. 35 (*c*). By changing the direction of the magnetic flux, the relation between the two voltages can be varied.

In the regulating-pole, or split-pole, converter, each pole consists of two parts, as shown in Fig. 38, a main part P and a regulating part P_1 separated by a narrow polar space s. Between these combination poles are wider polar spaces s_1, opposite which the brushes are placed. The illustration represents a two-pole machine, but the principle applies to multipolar machines also. When only the main poles are excited, the general direction of the lines of force is through the center lines of the main poles, as indicated by the line $o\,a$. If the excitation of the main poles is maintained constant and that of each regulating pole is increased in the same general direction as its main pole, the direction of the resulting flux swings toward the regulating pole, as indicated by the line $o\,b$; exciting the regulating pole in the opposite direction causes the resulting flux to swing toward the line $o\,c$. The direction of the resultant flux can thus be varied through a wide angle.

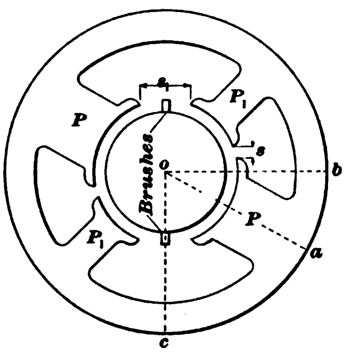


FIG. 38

This change in the direction of flux affects the ratio of voltage transformation, permitting a considerable range of direct-current voltage regulation with practically constant alternating voltage. Fig. 39 shows a 500-kilowatt, 240-300-volt regulating-pole rotary converter, in which *a* is a regulating pole and *b* a main.

84. Induction Regulator and Regulating Transformer.—Induction regulators and regulating transformers

are described in another Section. By means of either device, the voltage at the collector rings can be adjusted either manually or automatically, thus making corresponding adjustments of voltage at the commutator.

85. An **induction regulator** is a transformer with a primary core capable of being rotated inside the secondary core so that the primary flux threading the secondary coils can be adjusted at will. The primary winding is connected

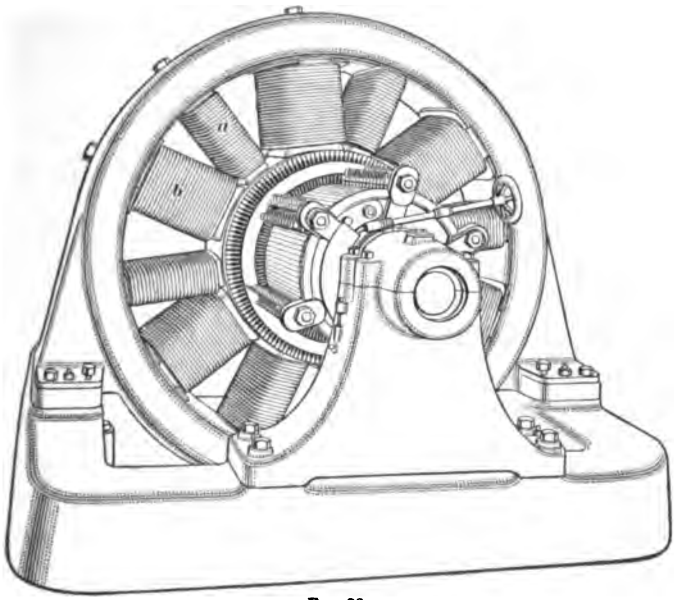


FIG. 39

in shunt across the circuit to be regulated, and the secondary winding is connected in series with the circuit. By adjusting the angular position of the primary core the secondary voltage can be boosted or lowered.

86. A **regulating transformer** is an ordinary static transformer provided with numerous taps on the secondary winding and a switching device by means of which the part of this winding in series with the circuit to be regulated can be adjusted; the primary winding is shunted across the circuit.

87. Direct-Current Booster.—A booster generator can be connected in series with the direct-current circuit, as in Fig. 40, and its voltage made to increase or decrease the voltage from the rotary converter. The booster can be shunt-wound and excited from the rotary, as shown, or series-wound. The booster is usually mounted on the same bedplate as the converter, and its armature shaft is continuous with the converter shaft or coupled to it. This combination is heavier, more expensive, and requires more space than the synchronous booster converter described in Art. 82, and, moreover, it is more troublesome, since two commutators must be maintained.

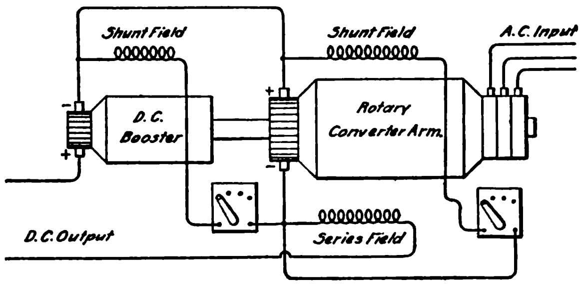


FIG. 40

88. Adjustment of Field Excitation.—The direct-current voltage of a rotary converter can be regulated within a very limited range by adjusting the field excitation. Changing the field excitation changes the phase relation of the alternating current and voltage, as explained in connection with synchronous motors; the nearer the alternating current and voltage are in phase, the higher will be the direct-current voltage. To increase the effect of change of field excitation, inductors are sometimes included in the alternating-current circuit or inductance is incorporated in the transformers. Voltage regulation by field adjustment is therefore at the expense of power factor. Adjustments can be made by means of a rheostat in the converter field, or a compound field winding can be used. Both are commonly employed, and the series field and inductors can be adjusted to keep the voltage constant from no load to full

load, *flat compounding*, or to increase the voltage with increasing load, *overcompounding*. Compound-wound converters do not operate satisfactorily in parallel with storage batteries; only shunt windings are advisable in such service.

DOUBLE-CURRENT GENERATORS

89. When a synchronous converter is used as a double-current generator, its output can be delivered as direct current, as alternating current, or partly as one and partly as the other, provided, of course, the combined output on the two sides does not exceed the capacity of the machine.

Double-current generators are sometimes useful where direct current is desired for utilization near at hand, and alternating current for transmission to distant points.

90. The heating effect and armature reaction in a double-current generator are much greater than in a synchronous converter delivering the same total output. In the converter armature conductors, the current is approximately the difference between the motor current and the generator current, and in the double-current generator, approximately the sum of the currents from both ends is effective, both in heating and in causing armature reaction. Compound field windings are common, but the shunt field is usually excited from a separate source, because, if self-excited, the demagnetizing action of lagging alternating current affects the voltage considerably.

INDUSTRIAL MOTOR APPLICATIONS

GENERAL CONSIDERATIONS

CHOICE OF SYSTEM

1. The successful operation of a motor depends on its intelligent selection and application. However good its design and construction, a motor will not give its best service in an application for which it is not suitable. Its general class, its type, its characteristics, its degree of enclosure and mechanical structure, each must be considered in making a selection.

Almost any industrial plant can be equipped with satisfactory motors operating on either of the two available systems, namely, alternating current or direct current. The choice between the two is influenced by the available supply of electricity, by the distance that electricity must be transmitted, and by the nature of the work to be done. Some general considerations are here given to guide in making a choice.

2. Available Supply.—In equipping with motors an industrial plant located in a territory served by a reliable central station, the use of central-station power is usually more satisfactory and economical than installing a private generating plant, though this is not always the case. In any event, the system chosen should agree with that of the central station, so that emergency service can be obtained. Most central stations are prepared to supply either alternating current or direct cur-

rent, but the latter is usually confined to comparatively small or thickly settled areas or to applications where it is peculiarly essential.

3. Distance of Transmission.—The energy loss in transmission circuits depends on the square of the current; therefore, long distance transmission at high pressure and low alternating current is more economical than at the low pressures common with direct current. The distance that direct-current energy can be transmitted economically depends on the voltage and on the quantity of energy. Energy at 500 to 600 volts is commonly transmitted 5 or 6 miles for electric railway work; 220-volt energy for industrial motors is limited to much smaller distances, possibly 1 mile, and 110-volt energy to approximately ½ mile. These limits are very approximate and are suggested only as guides; they must be varied according to the quantity of energy.

4. Nature of Work.—The work to be done may in some cases determine the choice of a system, because some work necessitates the characteristics of alternating-current motors and other work those of direct-current motors. These statements will be more fully explained later.

CHOICE OF MOTORS

5. Efficiency.—Efficiency is an important consideration in selecting motors, because the cost of energy varies inversely with the motor efficiency.

Let w = output, in watts, of a motor at efficiency e;
t = time, in hours, that motor operates;
c = cost of energy per kilowatt-hour;
C = total cost of energy.

Then,
$$C = \frac{w\,t\,c}{1{,}000\,e}$$

If a motor operates 10 hours per day and 312 days per year, the annual cost per horsepower output at 1 cent per kilowatt-hour is
$$C = \frac{746 \times 10 \times 312 \times .01}{1{,}000\,e} = \frac{\$23.275}{e}$$

Under these conditions the costs at different efficiencies ordinarily found in practice are as given in Table I. The annual cost per horsepower is proportional to the rate; thus, at 5 cents per kilowatt-hour, the values given in the table must be multiplied by 5.

TABLE I

COST OF ENERGY PER HORSEPOWER-YEAR

(312 days, 10 hours each, 1 cent per kilowatt-hour)

Efficiency	Annual Cost	Efficiency	Annual Cost	Efficiency	Annual Cost
.93	$25.03	.87	$26.75	.81	$28.73
.92	25.30	.86	27.06	.80	29.09
.91	25.58	.85	27.38	.79	29.46
.90	25.86	.84	27.71	.78	29.84
.89	26.15	.83	28.04	.77	30.22
.88	26.45	.82	28.38	.76	30.63

For example, suppose a motor is to be selected for an output of 10 horsepower, 10 hours per day, where the cost of energy is 5 cents per kilowatt-hour, and two motors having at this output efficiencies of 84 and 87 per cent., respectively, are available. The annual saving by using the motor with the higher efficiency is found by multiplying the difference between the figures in the table corresponding to these efficiencies by the horsepower and the rate.

At 84 per cent.	$27.71
At 87 per cent.	26.75
Difference	$ .96

Thus, $.96 \times 10 \times 5 = \$48$ per year saved.

6. Capacity.—At or near full rated load, a motor operates at its highest efficiency, and selection should be made accordingly. The motor should be capable of developing all the power required of it, but should not have a large surplus capacity. In general, the load should be from three-quarters to full rated motor capacity in order to obtain economical operation. A

motor operating at much less than three-quarter load generally has greater losses (lower efficiency) than a smaller motor operating at nearly full load, and the additional energy thus lost may soon equal in value the cost of a motor of suitable size.

When the load is of a varying nature, the motor must be large enough to carry the maximum load, although this maximum, if of not more than 1 or 2 hours' duration, can be carried as an overload on most motors rated for continuous duty. If the load is of very intermittent or periodic nature, a motor with appropriate rating can usually be obtained.

7. In selecting alternating-current motors, accuracy in determining capacities is especially important, because, at reduced capacities, such motors have both low efficiencies and low power factors. The power factor of a system on which a number of induction motors are operating at reduced loads may thus be made very low. The generators and the transmission circuits may be carrying full-load current, and a considerable portion of it may serve no useful purpose.

8. Speed.—As a general rule, a high-speed motor is less expensive than a motor for the same output at slow speed; therefore, a saving can be effected by selecting motors for the required outputs at speeds as high as can be used satisfactorily. Usually, the machine to be driven must operate at a specified speed, and the motor must be belted, geared, or otherwise connected to it in a way to obtain that speed. The motor speed must be such that this connection is practicable, and must not be too high for the safety of the motor itself.

9. Direct-Current Motors.—Direct-current motors are superior to alternating-current motors for some applications. For example, shunt-wound motors are preferable for applications requiring many speed adjustments with fairly constant speed at each adjustment; series-wound motors are superior for frequent starting with very high torque; and compound-wound motors for some applications requiring fairly high starting torque or occasionally heavy torque while operating.

TABLE II
INDUCTION-MOTOR APPLICATIONS

Squirrel Cage		Slip Ring	
Low Slip	High Slip	Constant Speed	Varying Speed

Blowers
  Centrifugal
  Disk
  Positive
Cement Machinery
  Crushers
  Grinders (various types)
Concrete mixers
Cotton-mill machinery
  Group drive
  Individual drive
Line-shaft drives
  Except for very large and heavy groups
Motor-generator sets
Paper-mill machinery
  Pulp grinders
  Pumps
  Jordans
  Stuff chests
Pumps
  Centrifugal
  Plunger
Wood-working machinery
  Except heavy planers, matchers, and band saws
	Cranes
	Cross-heads on machine tools
	Elevators
	Flywheel service
	  Punches
	  Shears
	  Large band saws
	  Motor-generator
	  Equalizer sets
	Laundry extractors
	Starting motors
	  Motor-generator sets
	  Rotary converters
	Sugar centrifugals
	Valves and gates
		Compressors
		  Starting against full pressure
		Flour-mill machinery
		  Group drive
		Line-shaft drive
		Large groups
		Paper-mill machinery
		  Beaters
		Pumps
		  Large plunger
		  Pumps starting against full pressure
		Woodworking machinery
		  Large band saws
		  Large planers and matchers
			Cement machinery
			  Dryers
			  Kilns
			Coal and ore unloaders
			Cranes
			Dredging machinery
			Elevators
			Flywheel service
			  Motor-generator sets
			  Equalizer sets, etc.
			Hoists and winches
			Paper-mill machinery
			  Newspaper machines
			  Supercalenders
			Shovels
			Steel-mill machinery
			  Charging machinery
			  Skip hoists

10. Alternating-Current Motors.—In comparison with direct-current motors, alternating current motors are generally more simple in construction, more durable, and require less attention while operating. With a few exceptions they are equally well suited to the work and in many cases are better. When alternating-current motors are selected, the merits of single-phase and polyphase motors and of the subdivisions of each of these two general classes must be considered.

11. Single-phase motors are generally applicable for industrial purposes only in small sizes up to 10, or possibly 15, horsepower. Starting rheostats are generally necessary with such motors of 5 horsepower and larger in order to keep the starting current low enough not to disturb the line voltage. Single-phase motors are available with different characteristics, some suitable for strictly constant-speed service and others for service where some speed variation is essential.

12. Polyphase motors include induction motors of the squirrel-cage type suitable for light-starting and constant-speed service, and the slip-ring type suitable for heavier-starting and for varying-speed service; they also include synchronous motors appropriate for light-starting and constant-speed service and for power-factor correction.

Squirrel-cage motors with low rotor resistance, resulting in low slip and correspondingly high efficiency are suitable for constant-speed applications where starting is fairly easy. For applications requiring more starting torque squirrel-cage motors with high rotor resistance, high slip, and correspondingly low efficiency are more appropriate. Table II gives a general idea of the selection of polyphase motors for many services.

GROUP DRIVE AND INDIVIDUAL DRIVE

13. Arranging several machines to receive power from a shaft driven by a single motor is called **group drive**. Operating each machine by a separate motor is called **individual drive.** Group drive is the original method, since the substitution of a motor for an engine to drive a line shaft was easily made; the

group then included all the machines formerly driven by a single engine. But long line shafts must be carried in many bearings with some friction loss in every bearing, especially if the shaft is not kept in perfect alinement, which is a difficult thing to do. Moreover, the shaft must run continuously, even though the various machines are used infrequently.

14. Subdivision of the machines into small groups, each belted from a comparatively short shaft driven by a smaller motor is more economical than the single large motor plan, because each motor need operate only when one of its machines is in use. For many purposes, however, the most rapid production and the greatest economy in time and in the use of energy are obtained when each machine is driven by its individual motor. In any case, whether for group drive or individual drive, the motor selected should be neither too small nor too large; its application should be such that it will not operate for long periods at a small fraction of its rated capacity. If several machines can be grouped and driven by one motor so as to utilize from three-fourths to full motor rating while the motor is running, group drive may be found economical; but if only one or two machines operate simultaneously taking less than half the power of which the motor is capable, a smaller motor on each machine will usually give better results. The choice between group drive and individual drive depends so entirely on local conditions that no specific rules can be given.

LOAD FACTOR

15. Load factor is the ratio of average load to maximum load; the term may be used in connection with a single motor or a whole plant in which many motors are operating. The average load, or power, is the total energy in kilowatt-hours used during a given period divided by the number of hours in the period. The maximum load may be considered as the motor rating in the case of a single motor, or the sum of all the motor ratings in a plant; or the maximum load may be measured by wattmeter or a maximum demand indicator. The

method requiring consideration of motor ratings is more common, because these ratings are easily read from the name plates; this method is less accurate, however, than that requiring actual measurement of maximum load.

Low load factor in an industrial plant indicates that some of the motors are standing idle, or possibly running with light loads part of the time. In very few plants is it possible to operate all the motors continuously at their full rated loads or at any constant load. For example, in most wood-working shops the machines are run only occasionally, and the load factor is sometimes as low as 5 per cent.

16. Knowledge of the load factor is of great value in estimating the quantity of energy required for a proposed motor installation. For example, if it is found that several motors aggregating 75 horsepower will be required to drive the machines in a planing mill that is to operate 10 hours per day, energy estimates based on 75 horsepower and 10 hours would be entirely too high. The load factor of many such plants is approximately 10 per cent., indicating that the average power requirement in this particular mill will probably be at the rate of only $75 \times .1 = 7\frac{1}{2}$ horsepower.

17. Load factors can be determined only by experience with many motor installations; these factors vary so widely for installations of any given nature that they must be used with great discretion. The busier a shop, the more nearly continuous will be the power requirement and the higher the load factor; hence, the load factor of any shop is higher at some seasons than at others.

18. The load factors in Table III are a guide in estimating the quantity of electric energy that will be required by motors in other similar industries. These load factors are average results obtained by observation in many plants; they are based on continuous operation, 8,760 hours (24×365) per year and on maximum load equal to the sum of the motor ratings. To use these factors in connection with a proposed installation of motors, estimate first the motor required for each machine or

TABLE III

AVERAGE LOAD FACTORS

(From The Electrical Solicitors Handbook, National Electric Light Association)

Service	Load Factor Per Cent.	Service	Load Factor Per Cent.
Bakeries	12	Laundries	20
Bed Mfg. (brass and iron)	20	Leather	8.5
Belt manufacturing	10	Lithographing	10
Blacksmith shop	15	Machine shops, group	20
Boiler shop, group	18	Machine shops, individual	8
Boiler shop, individual	8	Marble works, group	18
Bookbinders	9	Marble works, individual	10
Boots and shoes, group	25	Mattress manufacturing	6
Boots and shoes, individual	17	Newspapers, group	18
Bottling works	10	Newspapers, individual	8
Brass finishing	25	Ornamental iron works	17
Breweries	45	Paint manufacturing	25
Broom manufacturing	15	Packers	25
Brush manufacturing	7	Paper-box manufacturing	18
Butchers, group	15	Pipe threading and cutting	8
Butchers, individual	9	Plumbing	20
Can Manufacturing	30	Pottery manufacturing	13
Candy Mfg., group	18	Printing (job) group	18
Candy manufacturing, individual	9	Printing (job) individual	7
		Printing (magazine)	20
Carpet cleaning	15	Refrigeration	50
Carpet weaving	17.5	Restaurants	20
Cement mixing	10	Rock crushing	18.5
Chemical works	11	Rubber manufacturing	9.5
Cigar boxes	6	Saw manufacturing	30
Clothing manufacturing	18	Screw manufacturing	30
Coffee roasting and grinding	7	Seed cleaners	18
Coopers	5.5	Sheet-metal works, group	15
Creameries	20	Sheet-metal workers, individual	10
Diamond cutting and polishing	13.5	Silversmiths	7
Dye works	15	Soap manufacturing	20
Electroplating	20	Spice-grinding group	12
Electrotypers	20	Spice-grinding, individual	8
Feather cleaners	12	Stone working	6
Feed grinders	6	Structural-steel manufacturing, group	20
Fertilizer manufacturing	75		
Flour mills	23	Structural-steel manufacturing, individual	12
Forge shops	10		
Foundries, brass	6	Tannery	20
Foundries, group	15	Telephone stations	25
Foundries, individual	9	Textile mills	25
Glass grinding, polishing	17	Tinsmiths	10
Glove manufacturing	25	Tobacco	14
Glue manufacturing	15	Twine mills	30
Grain elevators	10	Wagon builders	5
Grocers, wholesale	15	Wall-paper manufacturing	12
Harness shops	10	Wheelwright	9
Hoisting and conveying	10	Woodworking, box making	10
Ice-cream manufacturing	20	Woodworking, furniture	28
Ice making	30	Woodworking (general), group	18
Ink making	23		
Jewelry	15	Woodworking (general), individual	6
Knitting mills	25		

each group of machines, multiply the sum of the motor ratings in horsepower by 746 to reduce to watts, the watts by 8,760, and this product by the load factor for that particular industry to give the probable energy output in watt-hours per year. This output must be divided by the average motor efficiency and by 1,000 to give the probable input in kilowatt-hours per year.

For example, suppose individual motor drive is to be installed in a general woodworking plant and that the sum of the ratings of all the motors is 50 horsepower. If all the motors were operated continuously at full rating, the energy required in a year, 8,760 hours, would be $\frac{50\times746\times8,760}{1,000\,e}=\frac{326,748}{e}$ kilowatt-hours, in which e is the average efficiency of all the motors. However, experience with similar plants has shown that only 6 per cent. of this energy will be required (load factor 6 per cent. from table); thus, if it is assumed that the average efficiency is 80 per cent., the probable annual energy requirement will be $\frac{.06\times326,748}{.8}=24,506.1$ kilowatt-hours, an average of approximately 2,042 kilowatt-hours per month.

FLYWHEELS

19. Mounting a heavy iron wheel, called a **flywheel,** on the shaft of a motor driving a fluctuating load lessens the maximum load on the motor and makes possible the use of a smaller motor than would be required without a flywheel. This statement applies only to motors driving loads that are subject to frequent and sudden changes; for example, some machine tools. The flywheel absorbs energy when the motor speed is high, as during times of light load, and gives it up when the motor slows down on account of heavy load, thus helping the motor carry the load peaks.

For best results, the motor speed must change considerably when the load changes, or, in other words, the speed regulation of the motor must be poor, in order to take advantage of the flywheel effect. This is the case with compound direct-current motors and with induction motors having high rotor resistance.

Such motors are also capable of exerting the torque necessary to start the flywheel and accelerate its speed.

20. The design of flywheels is practically always based on service conditions and very seldom falls to the lot of an operating engineer. In order that the flywheel may be properly designed, the exact service conditions should be specified, including, if possible, a curve showing the load fluctuations. Sometimes a spare motor can be connected to a load temporarily and a graphic wattmeter used to obtain a record of the load conditions. Such instruments are described in another Section.

MECHANICAL CONNECTIONS

21. When the motor and its load are to rotate in the same direction and at the same speed, the connection may be made *direct* by coupling the motor shaft to the driven shaft or by using one continuous shaft carrying the rotating elements of both the motor and the driven machine. This drive is positive because no slippage can occur. When the direction of rotation or the speed of the motor and the driven machine differ, some form of *indirect connection* must be used, the chief forms being ropes, chains, belts, and gears.

ROPE DRIVE

22. Rope drive consists of one or more endless loops of rope running in grooves on the faces of pulleys, usually called *sheaves*. This drive is increasing in popularity, especially for power installations of 200 horsepower upwards. The advantages claimed for it over other forms of mechanical connections are: (1) ability to transmit energy for long distances and in any direction; (2) smooth and quiet running; (3) absence of electrical disturbance (belts generate static charges); (4) economy in first cost and in maintenance; and (5) practical absence of slip.

23. Rope drive is of two general classes, *multiple* and *continuous*. **Multiple drive** consists of several independent

loops of rope running side by side on the sheaves. **Continuous drive** consists of only one long loop of rope wrapped several times around the driving and driven sheaves, thus filling the grooves from one side of the sheaves to the other, whence the rope is returned over guide sheaves and an idler, called a *tension sheave*, to the opposite side again, as shown in Fig. 1. The tension sheave is usually arranged to travel a limited distance so as to take up the slack as the rope stretches. There are several ways of arranging the tension sheave other than the way shown in Fig. 1.

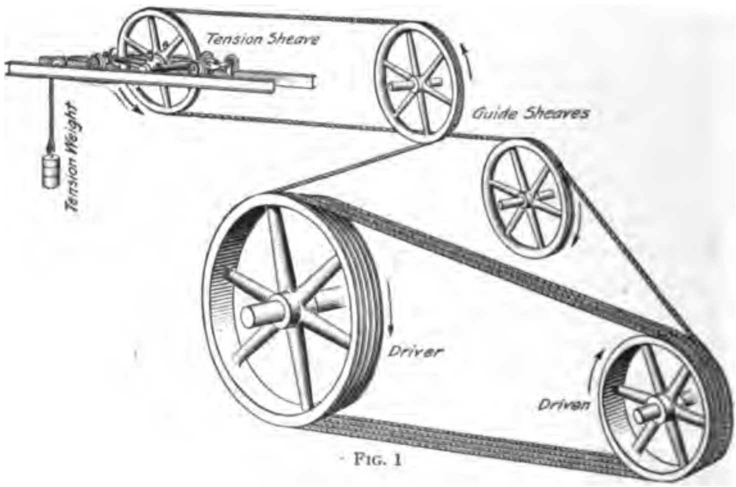


FIG. 1

24. Transmission ropes are made of wire, of cotton fiber, and of manila fiber. *Wire rope* is suitable for transmitting large quantities of energy long distances where the rope is subjected to few turns around pulleys, as in cable railways. *Cotton rope* is suitable for comparatively small transmission systems over small sheaves, but *manila rope* is best for the great majority of rope transmissions because of its superior strength and durability.

25. Manila Transmission Rope.—The information in Table IV can be used in selecting manila-rope sizes and speeds and sheave diameters. The power that each rope can transmit

TABLE IV

CAPACITY OF EACH MANILA TRANSMISSION ROPE WITH 180 DEGREES ARC OF CONTACT

Diameter of Rope Inches	Speed of Rope, in Feet per Minute										Minimum Diameter Smallest Sheave Inches
	1,500	2,000	2,500	3,000	3,500	4,000	4,500	5,000	6,000	7,000	
	Horsepower										
$\frac{1}{2}$	1.45	1.9	2.3	2.7	3.0	3.2	3.4	3.4	3.1	2.2	20
$\frac{5}{8}$	2.3	3.2	3.6	4.2	4.6	5.0	5.3	5.3	4.9	3.4	25
$\frac{3}{4}$	3.3	4.3	5.2	5.8	6.7	7.2	7.7	7.7	7.1	4.9	30
$\frac{7}{8}$	4.5	5.9	7.0	8.2	9.1	9.8	10.8	10.7	9.3	6.9	36
1	5.8	7.7	9.2	10.7	11.9	12.8	13.6	13.7	12.5	8.8	42
$1\frac{1}{4}$	9.2	12.1	14.3	16.8	18.6	20.0	21.2	21.4	19.5	13.8	54
$1\frac{1}{2}$	13.1	17.4	20.7	23.1	26.8	28.8	30.6	30.8	28.2	19.8	60
$1\frac{3}{4}$	18.0	23.7	28.2	32.8	36.4	39.2	41.5	41.8	37.4	27.6	72
2	23.1	30.8	36.8	42.8	47.6	51.2	54.4	54.8	50	35.2	84

increases at increased speed up to 4,500 or 5,000 feet per minute, beyond which the power decreases owing to the effect of centrifugal force and air resistance. In general, the rope speed for maximum economy should be from 4,000 to 4,500 feet per minute. Large sheaves with few ropes, or few turns of rope, are usually preferable to smaller sheaves and more ropes. Ropes having a diameter greater than $1\frac{3}{4}$ inches are seldom used except in very large transmissions, say 1,000 horsepower and more.

CHAIN DRIVE

26. Chain drive consists of an endless chain running over sprocket wheels, as on a bicycle. The links are made to fit accurately over the sprockets, so that no slipping can occur. The speed of each sprocket wheel is inversely proportional to its diameter or to its number of teeth.

Let s = speed of motor sprocket;
d = diameter of motor sprocket;
t = number of teeth in motor sprocket;
S = speed of driven sprocket;
D = diameter of driven sprocket;
T = number of teeth in driven sprocket.

Then,
$$\frac{s}{S} = \frac{D}{d} = \frac{T}{t}.$$

For example, a motor running at 1,000 revolutions per minute can be used to drive a machine at 100 revolutions per minute by using a 3-inch sprocket on the motor shaft and a 30-inch sprocket on the driven shaft of the machine, because $\frac{1{,}000}{100} = \frac{30}{3}$.

Chain drive is useful for large speed reductions between close centers. It is sometimes preferable to gear drive on account of being more quiet in operation.

BELT DRIVE

27. Belt drive is probably the most common method of connecting motors to their loads, especially motors of small and medium sizes. In order to use it, the distance between the driving and the driven shafts must be enough to allow some belt sag, and the slack side should be above, as indicated in Fig. 2, so that the belt will more fully wrap and cling to the pulleys. One pulley should never be located directly over the other if avoidable; for best results, the angle between the horizontal and a line connecting the two pulley centers should not exceed 45°. Some provision is generally necessary for adjusting the belt tension. This provision is usually a screw device for sliding the motor on rails, but in some cases idler pulleys are pressed against the slack side of the belt, as indicated at I, Fig. 2, by a spring or by a weight.

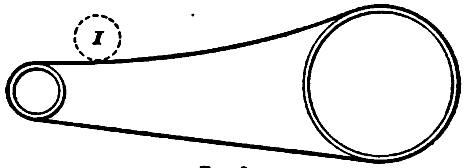


Fig. 2

28. Calculations.—In a belting problem, the speed of the machine to be driven is generally known, and pulleys should be selected so as to allow the highest practicable motor speed, in order to reduce the motor cost.

Let d = diameter of motor pulley;
s = speed of motor pulley;
D = diameter of driven pulley;
S = speed of driven pulley.

Then,
$$\frac{d}{D} = \frac{S}{s}$$

If the speed S of the driven machine is the only known value, the other three can be chosen within the limits of good engineering practice. For example, if the machine must run at 250 revolutions per minute and its pulley is 20 inches in diameter, S and D in the foregoing formula are fixed. If a motor running at 1,150 revolutions per minute is available, then $\frac{d}{20} = \frac{250}{1,150}$ and

$d=4.35$ inches. As pulleys with fractional diameters smaller than $\frac{1}{2}$ inch are rarely used, a $4\frac{1}{2}$-inch pulley would probably be selected in this case, giving a machine speed $S=\frac{4\frac{1}{2}\times 1{,}150}{20}$ $=258.75$ revolutions per minute. If the machine speed is desired more nearly 250 revolutions per minute, use may be made of a $4\frac{1}{2}$-inch motor pulley and a 21-inch machine pulley, which give 247 revolutions per minute, or a 5-inch motor pulley and a 23-inch machine pulley, which give 250 revolutions per minute. If a cheaper motor is desired, a 4-inch motor pulley and a 28-inch machine pulley would allow a motor speed of 1,750 revolutions per minute because $\frac{4}{28}=\frac{250}{1{,}750}$.

29. The **power** that a belt can transmit safely depends on its speed, its thickness, its width, on the arc of contact between the belt and the smaller pulley, and on the material of which the belt and the pulley are made.

The belt speed is the rate at which any point on the belt moves; this rate is the product of the circumference of either pulley and the number of revolutions of the pulley per minute. With the letters d, D, s, and S representing the same quantities as in Art. **28**,

$$\textit{belt speed in feet per minute}=\frac{\pi d s}{12}=\frac{\pi D S}{12}$$

30. Best results are usually obtained with belt speeds between 3,000 and 5,000 feet per minute; speeds above 5,500 feet per minute are not good practice. For example, if the driven pulley must run at 500 revolutions per minute and a belt speed of approximately 4,500 feet per minute is desired, substitution of these values in the formula gives

$$4{,}500=\frac{\pi D\times 500}{12}, \text{ or } D=\frac{12\times 4{,}500}{500\pi}=34 \text{ inches, approx.}$$

A 34-inch pulley would give 4,450 feet per minute, and a 36-inch pulley 4,712 feet per minute; either pulley; or even a 38-inch pulley giving nearly 5,000 feet per minute, would be good practice.

31. Belt thickness is specified as *single*, *double*, and *triple*. The transmitting capacity of belts is sometimes expressed in speed per minute at which 1 horsepower per inch width can be carried. This speed is approximately as follows: For single belts, 750; for double belts, 450; and for triple belts, 350. The capacity is directly proportional to the speed and the width; thus a 4-inch single belt running at 4,500 feet per minute can transmit $4{,}500 \div 750 = 6$ horsepower per inch width or $4 \times 6 = 24$ horsepower total.

32. The **arc of contact** of the belt with the smaller pulley is the only one that need be considered, since the belt will not slip on the larger pulley. This arc depends on the difference between the diameters of the two pulleys and on the distance between pulley centers. If the pulleys have equal diameters, the belt will wrap approximately one-half of each pulley surface, or the arc of contact will be 180°. In any case, the arc of contact for the small oulley can be found by the formula

$$arc = 180° - 2 \sin^{-1} \frac{D-d}{24\,L},$$

in which d = diameter of small pulley, in inches;
D = diameter of large pulley, in inches;
L = distance between pulley centers, in feet.

The expression $2 \sin^{-1} \frac{D-d}{24\,L}$ means *two times the angle whose sine is* $\frac{D-d}{24\,L}$. After the value $\frac{D-d}{24\,L}$ has been determined, the corresponding angle can be found in the Table of Natural Sines, Cosines, Tangents, and Cotangents accompanying *Practical Mathematics*, Part 5. Approximate results are sufficiently accurate for practical purposes.

EXAMPLE.—Find the arc of contact of a belt on a 10-inch pulley belted to a 32-inch pulley with a distance of 12 feet between pulley centers.

SOLUTION.—According to the formula,

$$\text{arc} = 180° - 2 \sin^{-1} \frac{32-10}{24 \times 12} = 180° - 2 \sin^{-1} .0764$$

From the table of natural sines and cosines, .0764 is the sine of 4° 23′ and $2 \times 4° 23' = 8° 46'$; then,

$$\text{arc} = 180° - 8° 46' = 171° 14'. \quad \text{Ans.}$$

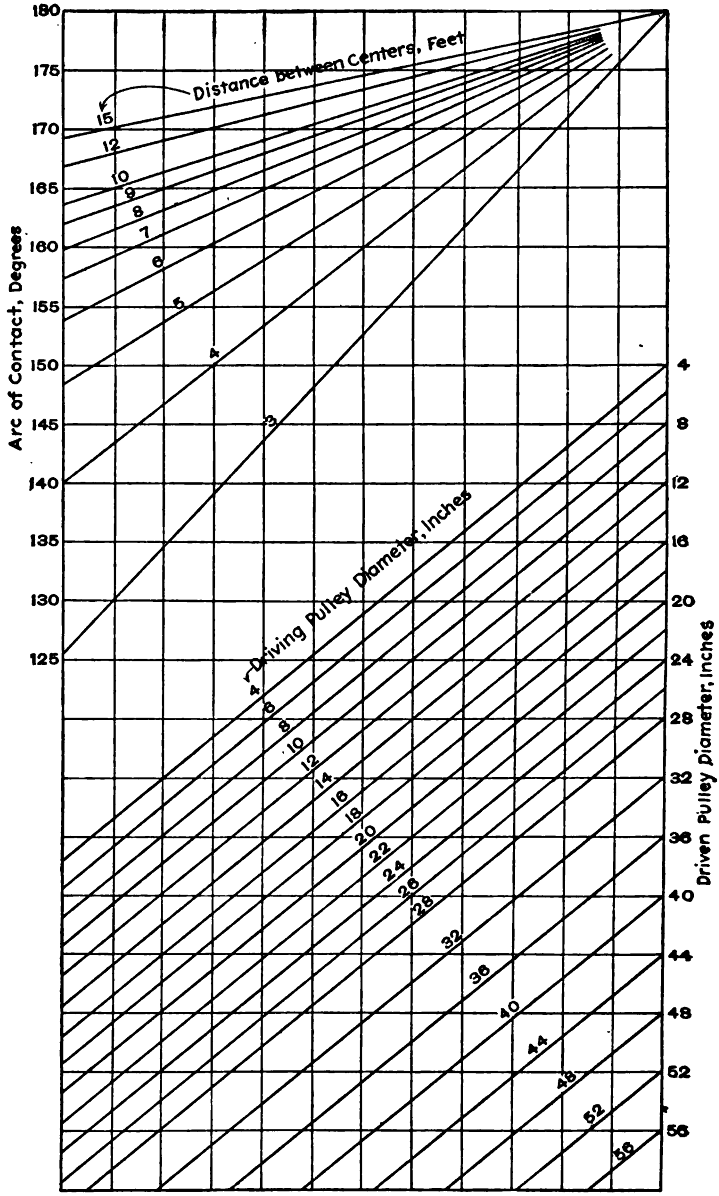

Arc of Contact, Degrees
180
175
170
165
160
155
150
145
140
135
130
125
Distance between Centers, Feet
15
12
10
9
8
7
6
5
4
3
Driving Pulley Diameter, Inches
4
6
8
10
12
14
16
18
20
22
24
26
28
32
36
40
44
48
52
56
Driven Pulley Diameter, Inches
4
8
12
16
20
24
28
32
36
40
44
48
52
56

Fig. 3

33. Fig. 3 shows a chart by means of which the arc of contact of a belt on the smaller of two pulleys can be readily determined when the pulley diameters and their distance apart are known. For example, to determine the arc of contact on a 10-inch pulley belted to a 32-inch pulley with 12 feet between pulley centers, find 32 on the right-hand margin and horizontally to the left find a point on the oblique line representing a 10-inch driving pulley; vertically above this point find a point on the oblique line representing 12 feet between centers, and horizontally to the left of this latter point find on the margin the value of the arc of contact, approximately 171°. This chart is accurate enough for practical purposes and includes data for the pulleys in most common use.

34. Fig. 4 shows a chart representing the interrelations of pulley diameter, motor speed, belt travel, arc of contact, and horsepower per inch width of leather belt for different belt thicknesses on iron pulleys. This chart is based on the figures previously given herein, and belts selected by it will conform to established practice. For paper pulleys, add 30 per cent. to the horsepower values given by the chart. For four-ply canvas or rubber belt, use the value for single leather belt. The use of the chart is best explained by an example.

Assume that 10 horsepower is to be transmitted from a 10-inch pulley running at 1,000 revolutions per minute, by a single leather belt with an arc of contact of 170°. To determine the width of belt required, first find the pulley diameter 10 on the lower left-hand margin of Fig. 4 and horizontally to the right find a point on the oblique line marked 1,000 *R.P.M.* From this point proceed vertically upwards to the horizontal line near the center of the chart representing 180° arc of contact, thence follow the oblique line downwards to the horizontal line representing 170° arc of contact, then vertically upwards to the oblique line marked $\frac{7}{32}$-*inch single belt*, and then horizontally to the left, where approximately 3.1 horsepower per inch width of belt is found. For 10 horsepower, the belt must be $10 \div 3.1$, or slightly over 3 inches wide; a 4-inch belt would probably be used. The width of the pulley faces should be a little greater

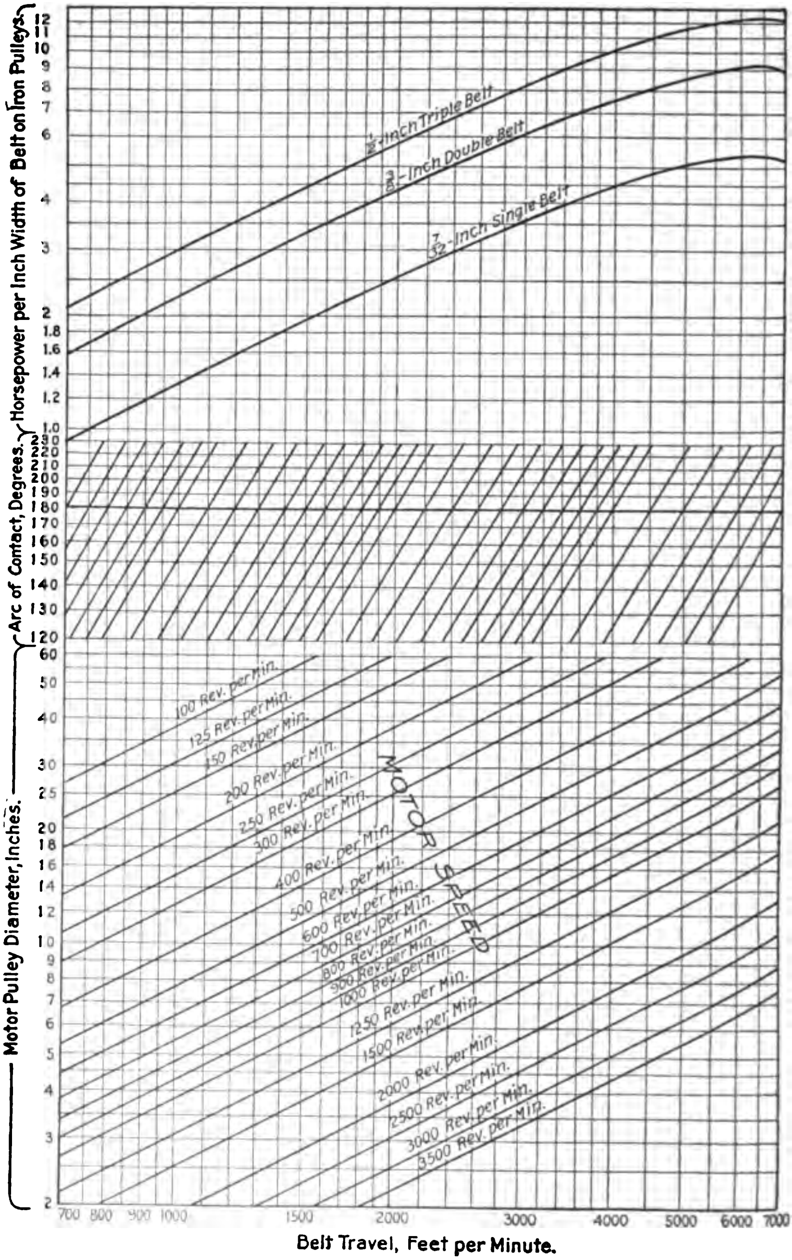

Horsepower per Inch Width of Belt on Iron Pulleys
Arc of Contact, Degrees.
Motor Pulley Diameter, Inches.
1/2-Inch Triple Belt
3/8-Inch Double Belt
7/32-Inch Single Belt
MOTOR SPEED
100 Rev. per Min.
125 Rev. per Min.
150 Rev. per Min.
200 Rev. per Min.
250 Rev. per Min.
300 Rev. per Min.
400 Rev. per Min.
500 Rev. per Min.
600 Rev. per Min.
700 Rev. per Min.
800 Rev. per Min.
900 Rev. per Min.
1000 Rev. per Min.
1250 Rev. per Min.
1500 Rev. per Min.
2000 Rev. per Min.
2500 Rev. per Min.
3000 Rev. per Min.
3500 Rev. per Min.
Belt Travel, Feet per Minute.

Fig. 4

than the width of the belt; a 5-inch pulley face would do here, though a 6-inch face would be better because it would allow 1 inch play of belt each way.

SPUR-GEAR DRIVE

35. When a motor and its driven machine operating at different speeds are mounted close together, **spur gearing** is often the best method of mechanical connection. A pinion on the motor shaft meshing with a gear-wheel on the driven shaft makes positive connection, and the ratio of speed reduction can be made high.

36. Fig. 5 shows most of the features of importance to consider in selecting gears. Two geared wheels running together have the same effect as would two smooth cylinders running together by friction only and without slipping. Such cylinders are called *pitch cylinders* and are represented on drawings of gear-wheels by the *pitch line*, which is the circumference of the *pitch circle*. The *circular pitch* is the distance along the pitch line between the centers of adjacent teeth. The *pitch diameter* is the diameter of the pitch circle; reference to the diameter of a pinion or gear always means pitch diameter unless otherwise specified. The **face** is the length of teeth parallel to the shaft. The *diametral pitch* is the number of teeth per inch of diameter. or the ratio of the number of teeth to the diameter in inches; for example, a 20-tooth pinion 5 inches in diameter has a diametral pitch of $20 \div 5 = 4$.

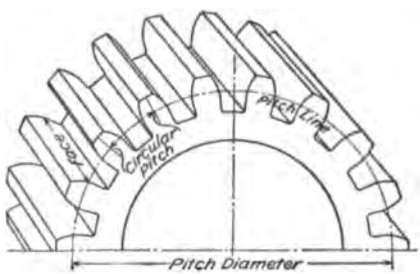


FIG. 5

37. Calculations.—The most important relations to be considered in gearing calculations may be expressed by means of formulas.

Let r = number of revolutions per minute of pinion;
R = number of revolutions per minute of gear;
d = pitch diameter, in inches, of pinion;
D = pitch diameter, in inches, of gear;
n = number of teeth in pinion;
N = number of teeth in gear;
p = diametral pitch of both pinion and gear;
p_1 = circular pitch of both pinion and gear;
L = distance, in feet, between shaft centers;
o = gear ratio, or ratio of speeds;
S = pitch line speed, in feet per minute.

Then,
$$o=\frac{N}{n}=\frac{D}{d} \qquad (1)$$
$$L=\frac{d+D}{2} \qquad (2)$$
$$p=\frac{n}{d}=\frac{N}{D} \qquad (3)$$
$$p_1=\frac{\pi d}{n}=\frac{\pi D}{N}=\frac{\pi}{p} \qquad (4)$$
$$S=\frac{\pi d r}{12}=\frac{\pi D R}{12} \qquad (5)$$

If the gear ratio and the number of teeth in either wheel or the diameter of either wheel are known, the corresponding number for the other wheel can be found by formula **1.** For example, if the gear ratio is 6 and the pinion has 22 teeth, the gear must have $6\times 22=132$ teeth ($N=o\,n$); if the pinion in this case is $2\frac{3}{4}$ inches in pitch diameter, the gear must be $6\times 2\frac{3}{4}=16\frac{1}{2}$ inches diameter ($D=o\,d$).

In the problem just assumed, the distance L between shaft centers must be $\frac{16\frac{1}{2}+2\frac{3}{4}}{2}=9\frac{5}{8}$ inches, according to formula **2**; the diametral pitch p is $22\div 2\frac{3}{4}$ or $132\div 16\frac{1}{2}=8$, according to formula **3**; the circular pitch p_1 is $\frac{3.1416}{8}=.3927$ inch, according to formula **4**, and the pitch line speed S, is $\frac{3.1416\times 2\frac{3}{4}}{12}\,r$ or

$\frac{3.1416 \times 16\frac{1}{2}}{12} R$, according to formula **5.** The pitch line speed in feet per minute can thus be determined as soon as r or R is known.

38. For satisfactory service in most applications, motor gears should be strong, durable, and quiet in operation. The first two of these requirements, and to some extent the third, are attained by selecting a pinion with the proper face, diameter, and diametral pitch. Gears selected in accordance with the chart, shown in Fig. 6, will meet all ordinary requirements. This chart is based on the use of gear dimensions directly proportional to the motor torque, that is, to the strength required, and gives proper dimensions for steel pinions; the face of a rawhide pinion should be 25 per cent. longer than that of a steel pinion for the same work.

To illustrate the use of the chart, assume that a pinion is required for a 5-horsepower motor running at 1,200 revolutions per minute. Find the intersection of the oblique line marked 5 *H.P.* with the horizontal line representing 1,200 revolutions per minute, and vertically under this intersection near the lower edge of the chart find approximately 22 pound-feet torque (pounds at 1 foot radius), 2.3-inch pinion face, and 3.2-inch pitch diameter; on the same vertical line at the top of the chart find the diametral pitch 4.85. The figures cannot always be used exactly as given in the chart, because some of the fractional dimensions are impracticable. Fractional face dimensions smaller than $\frac{1}{4}$ inch are seldom used, and in the example just given a $2\frac{1}{4}$-inch face would be good practice. The diametral pitch for small pinions is usually a whole number, and in this case a pitch of 5 would probably be used; the pitch diameter can remain 3.2, as given by the chart, because the number of teeth will then be $5 \times 3.2 = 16$.

For motors in very heavy service, such as that for which series motors, heavily compounded motors, and slip-ring induction motors are frequently employed, the pinion face as found by the chart should be increased approximately 50 per cent. in order to give the required strength.

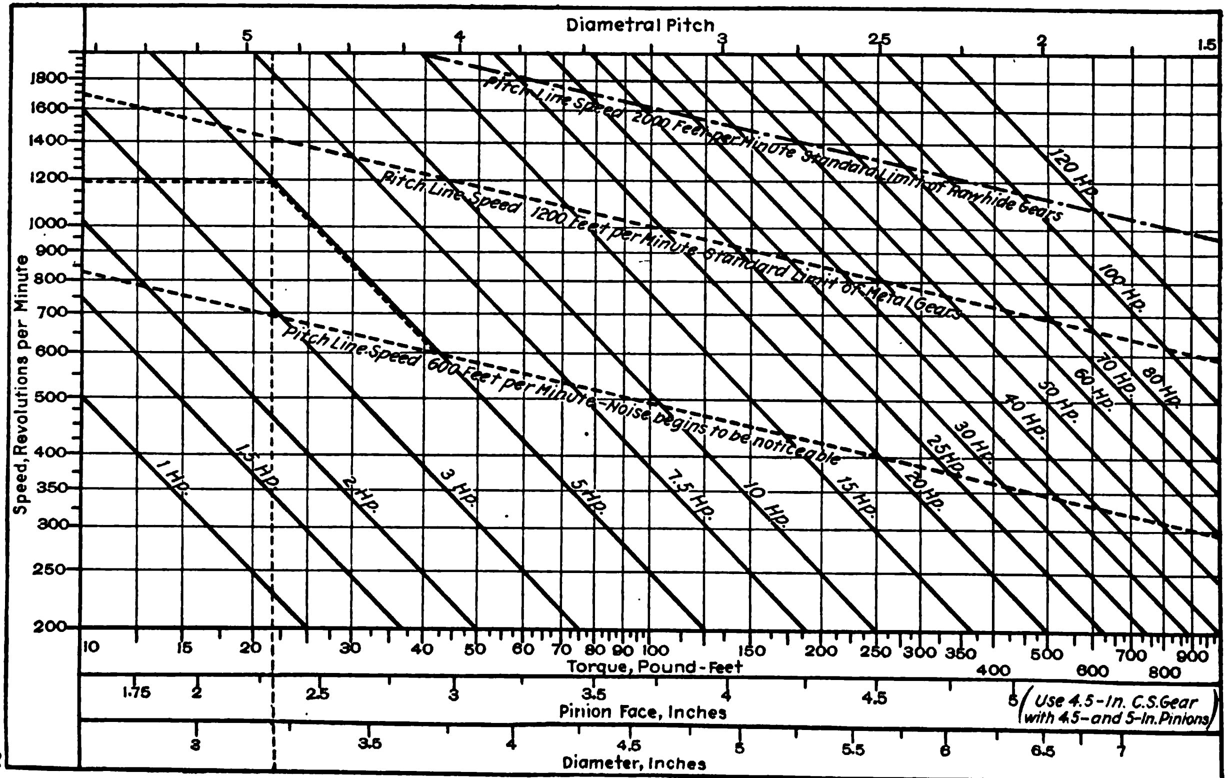

Diametral Pitch
Speed, Revolutions per Minute
Torque, Pound-Feet
Pinion Face, Inches
Diameter, Inches
Pitch Line Speed 2000 Feet per Minute Standard Limit of Rawhide Gears
Pitch Line Speed 1200 Feet per Minute Standard Limit of Metal Gears
Pitch Line Speed 600 Feet per Minute-Noise begins to be noticeable
1 Hp.
1.5 Hp.
2 Hp.
3 Hp.
5 Hp.
7.5 Hp.
10 Hp.
15 Hp.
20 Hp.
25 Hp.
30 Hp.
40 Hp.
50 Hp.
60 Hp.
70 Hp.
80 Hp.
100 Hp.
120 Hp.
(Use 4.5-In. C.S. Gear with 4.5- and 5-In. Pinions)

FIG. 6

39. Gears.—With steel pinions, the gear face is usually the same as the pinion face, and the material is generally cast iron for light and medium heavy service. The diametral pitch and circular pitch are necessarily the same for both gear and pinion in order to make them mesh properly; the gear ratio being known, the gear diameter depends on the pinion diameter in accordance with formula **1**, Art. **37**, in which $D = o\,d$. Cast steel is much stronger than cast iron and is frequently used for gears where the face of a cast-iron gear would be $4\frac{1}{2}$ inches or more.

40. Noise.—An objection to gears for many applications is their noisy operation. This noise is caused by vibration and is least when the pitch-line speed is low, also when the foundation of the motor and the driven machine is firm and rigid, and when the pinion is mounted close to the motor bearing. An additional bearing outside the pinion lessens vibration and noise. and is a necessity with large motors or in heavy service. The noise comes mostly from the gear-wheel; the pitch of this noise is higher and its penetrating power greater with a large number of fine teeth than with fewer and coarser teeth.

With steel pinions and cast-iron gears, noise is not usually objectionable at pitch-line speeds below 1,200 feet per minute. With rawhide pinions, this limit can be made, 2,000 or sometimes 3,000 feet per minute without serious noise; for best results, the gear should come in contact with only the rawhide and not with the metal flanges of the pinion.

WOODWORKING

41. Woodworking machinery usually operates at fairly high speed and at constant speed. The starting conditions are not hard, except in the larger machines with considerable friction. The motors must be capable of operating in the midst of dust and shavings without great increase of fire hazard.

Squirrel-cage induction motors are best suited to this work on account of constant-speed characteristics and absence of sliding contacts. Shunt-wound direct-current motors are also

used, but they must usually be in entirely enclosed frames or in rooms separate from the driven machines. For starting the heavier woodworking machines, compound motors are sometimes preferable.

42. Power Required.—The power to drive any woodworking machine depends on the kind of wood to be worked, the rate of feed, the condition of the cutting tools, and the condition of the bearings and gears in the machine. For belt drive, the motor speed must not be too high to permit the use of a pulley of ample size, especially for a machine that has high static friction and is hard to start. In starting such a machine, the belt would be thrown off a pulley that is too small; moreover, the dry, dusty conditions in woodworking shops decrease the adhesion between pulleys and belts and necessitate liberal belt and pulley sizes.

No practicable method exists for calculating the power required to drive woodworking machinery; experimental data are essential in practically every case. Manufacturers of woodworking machines and of motors can always furnish estimates based on experiments, but conditions of application may vary enough to make these estimates inaccurate in some cases.

MACHINE TOOLS

43. Types of Motors Required.—Direct-current motors are best suited to the operation of machine tools requiring adjustable speed. A tool required to handle miscellaneous work with pieces of varying size and material must operate at different speeds for maximum economy. For example, in turning a piece, the lathe speed must be increased as the diameter of the work decreases in order to keep the cutting speed fairly constant; shunt motors are preferable for such applications. For machines having heavy parts to start or many bearings that make the friction high, compound motors are preferable; such motors should also generally be used on punch presses, shears, bending rolls, and similar machines where the torque is excessive for brief intervals.

Alternating-current induction motors are also much used for constant-speed machine-tool service, squirrel-cage motors where the starting conditions are comparatively easy, and slip-ring motors for machines that start hard. Induction motors with high secondary resistance are applicable in some cases where starting conditions or intermittent operating conditions are hard, provided good speed regulation is not essential.

Open-type motors are satisfactory in many cases, but if tools, chips, or loose materials of any kind are likely to get inside the motor, it should be semi-enclosed or fully inclosed, according to the nature of the substances to be excluded. Semi-enclosed motors are very frequently used for machine-tool applications.

With few exceptions, the motors for driving machine tools have horizontal shafts and are belted, coupled, or geared to the driven shaft of the tool. Chain drive is sometimes employed in preference to belts or gears when the center distance is small and the ratio of speed reduction large. Back gears and counter-shafts also are sometimes used, though ordinarily most of the speed reduction is provided for on the tool itself.

Machine-tool motors are rated for intermittent service, one or two hours at rated load with temperature rises within safe limits. Continuous operation of machine tools at steady loads during long continued periods is usually impracticable.

44. Motor Selection.—Each motor should be selected for the average power requirement, provided the maximum requirement, which usually occurs during the first, or *roughing*, cut does not exceed the overload capacity for which the motor is recommended. The duration of cut and the number of cuts in a given time must be considered in making the selection.

In general, the power required to drive a machine tool depends on three conditions: (1) The type and condition of the cutting tool employed; (2) the rate of removing metal; and (3) the kind of metal that is being cut.

45. All cutting tools employed on machine tools may be classified in three groups: (1) chisel-type tools used on lathes, boring mills, planers, and shapers; (2) drills and reamers; and (3) milling cutters.

46. Calculations.—The rate of removing metal in cubic inches per minute is the product of the cutting speed in inches per minute and the area of a cross-section of the cut in square inches. With tools of the first group, this area is the product of the depth of cut in inches and the feed, or width, of cut. If the area of cut and the cutting speed are known, the quantity of metal removed per minute can be readily determined by the aid of Fig. 7.

For example, suppose a cut $\frac{1}{4}$ inch deep with $\frac{1}{16}$-inch feed is being taken in a lathe on a steel shaft 3 inches in diameter rotating at 75 revolutions per minute. The area of cut is $\frac{1}{4}\times\frac{1}{16}=\frac{1}{64}$, or .0156 square inch approximately, or for practical purposes .016. The cutting speed is $\frac{3\pi}{12}\times 75=59$ feet per minute. A horizontal line from the number .015 on the left margin meets a vertical line from the number 60 on the lower margin at a point about central between the oblique lines marked 11 and 12, indicating that approximately 11.5 cubic inches of metal are removed per minute.

47. The rate at which a drill removes metal may be calculated by means of the formula

$$Q=.7854\,d^2 f,$$

in which Q = cubic inches per minute;
d = diameter of hole, in inches;
f = rate of feed, in inches per minute.

A milling machine removes metal at a rate equal to the product of the length and depth of cut in inches and the feed in inches per minute.

48. The approximate horsepower for machine tools is equal to the product of the cubic inches of metal removed per minute and a constant; that is,

$$\text{H. P.}=CQ$$

With chisel type tools, the constant C is from .3 to .5 for cast iron, .6 for wrought iron and machinery steel, 1 to 1.25 for steel .5 per cent. carbon and harder, and .2 to .25 for brass and similar alloys. With drills, these constants should

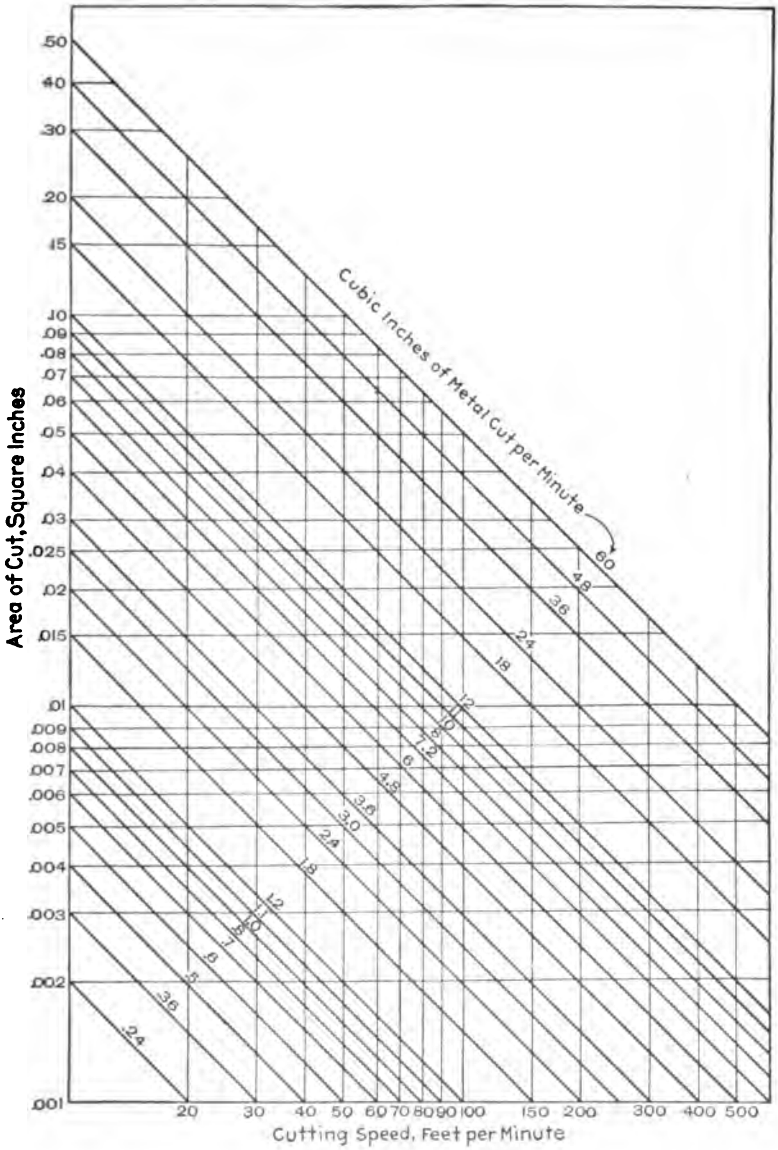

Cubic Inches of Metal Cut per Minute
60
48
36
24
18
12
11
10
8
7.2
6
4.8
3.6
3.0
2.4
1.8
1.2
1.1
1.0
.8
.7
.6
.5
.36
.24
Area of Cut, Square Inches
.50
.40
.30
.20
.15
.10
.09
.08
.07
.06
.05
.04
.03
.025
.02
.015
.01
.009
.008
.007
.006
.005
.004
.003
.002
.001
20
30
40
50
60
70
80
90
100
150
200
300
400
500
Cutting Speed, Feet per Minute

FIG. 7

be doubled. Vertical milling machines require approximately 1 horsepower and horizontal machines 1.6 horsepower per cubic inch of metal cut per minute. Small tools for light work or finishing require only enough power to start the machine and overcome its friction while running; usually ½, 1, or 2 horsepower is sufficient, according to the size of the machine.

For example, the lathe referred to in Art. **46** while removing 11 cubic inches from a steel shaft requires approximately $.6 \times 11 = 6.6$ horsepower. For cutting hard steel at the same rate, the maximum requirement would probably be $1.25 \times 11 = 13.75$ horsepower.

CRANES AND HOISTS

49. Specially constructed series-wound direct-current motors are most suitable for crane and hoist service, although special slip-ring motors are successfully used in some cases. The motor frames must be very heavy, substantial, and compact. The weight and substantial construction are necessary to resist the heavy stresses, and compactness is required for the limited space available for installing motors. The electrical design must be such that excessively heavy torque can be exerted for brief intervals, as is possible with series motors; if the friction load of a hoist is very light, the motor should also have enough shunt-field winding to prevent excessive speed when running idle.

50. Motor Characteristics.—The performance curves of a motor must be known before it can be applied intelligently to crane or hoist service. Fig. 8 shows curves of a 220-volt hoist motor by means of which the performance of the motor under any set of conditions can be foretold. For example, suppose a torque of 175 pounds at 1 foot radius, or 175 pound-feet, is required to operate a hoist. The performance of the motor with that torque is found by following the horizontal line corresponding to 175 pound-feet, as indicated on the right margin, until this line intersects the curve indicating torque. Then follow the vertical line through this intersection to the lower margin, finding 80 amperes, also upwards to its intersections

with the curves indicating horsepower, speed, efficiency, and time-temperature. From these intersections trace horizontally to the left margin for values of horsepower 20, speed 590 revolutions per minute and efficiency 83.5 per cent., and to the right for the time, approximately 35 minutes, during which the

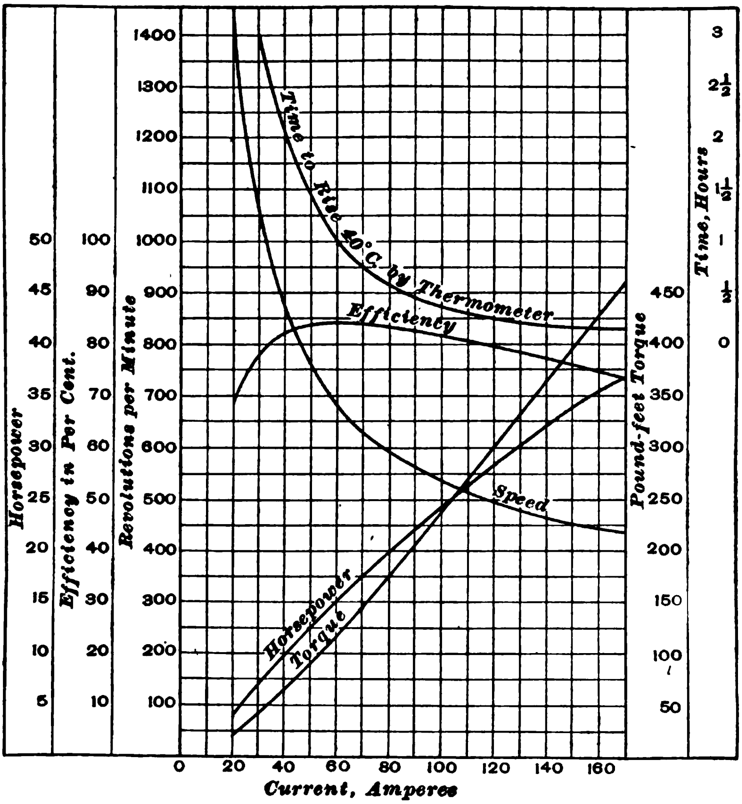


FIG. 8

motor can carry this load without showing a temperature rise higher than 40° C. in any part.

If this speed is too slow or if any other characteristic thus found is unsatisfactory, another motor must be selected. Torque and speed are the important characteristics of such

motors; rating them in horsepower is of little use for making selections. For example, the motor with performance indicated in Fig. 8 could develop a torque of 400 pound-feet with the following approximate characteristics, as shown by the curves: amperes, 150; horsepower, 34; speed, 450 revolutions per minute; efficiency, 76 per cent.; and time to rise 40° C., about 10 minutes.

PUMPS

51. The operation of pumps is an ideal application for electric motors, both direct current and alternating current. The load can be accurately calculated, the motor can be selected to operate at its most efficient load, and a pump load is usually continuous for considerable periods. The time of operation can often be selected when the power station is not fully loaded, and energy can therefore be supplied at reduced cost. A motor-driven pump can be located at the most advantageous position and operated from a distant point more convenient for an attendant, or it can be arranged for automatic operation resulting from the rise and fall of a float or the movements of the indicator of a pressure gauge.

52. Classes.—Pumps may be classed as *piston*, *plunger*, *centrifugal*, *rotary*, and *screw types*. In a **piston pump,** the piston carrying packing plays inside a cylinder. In a **plunger pump,** the plunger plays inside a cylinder with stationary packing rings. In both piston and plunger pumps, valves prevent movement of the liquid in the wrong direction, and the discharge is pulsating. By means of an air chamber the pulsations can be smoothed out into a steady stream, as from high-pressure fire pumps.

In a **centrifugal pump,** a rotating element, called an *impeller*, consisting of a series of blades, or vanes, sets the liquid in motion inside the fan casing, and stationary vanes guide this motion in the desired direction. The discharge is steady, or non-pulsating. In a **rotary pump,** the impeller consists of a series of chambers, or buckets, each of which impounds a

quantity of liquid and forces it through the discharge outlet, the action being so rapid that the discharge is a steady stream. In a **screw pump,** the blades are in the form of a spiral that, in turning, forces the material forwards.

53. Piston, plunger, rotary, and screw pumps are positive in action and are suitable for working against high pressures; screw pumps are especially suitable for handling semiliquid masses containing coarse particles not too large to pass between the blades. In general, centrifugal pumps are best suited for handling large quantities of liquid or semiliquid at comparatively low pressures, although pumps of this class are also made for operating at high pressures.

54. Pump Data.—The following information is approximately correct. One gallon (U. S.) of water contains 231 cubic inches and 1 cubic foot contains 7½ gallons. Fresh water weighs 8⅓ pounds per gallon, or 62½ pounds per cubic foot; sea-water weighs 64⅛ pounds per cubic foot.

Atmospheric pressure at sea level is 14.7 pounds per square inch. In a perfect vacuum, this pressure supports a column of mercury 29.9 inches high and a column of water 34.9 feet high. If a long tube, open at one end, is filled with mercury (quicksilver), inverted, and the open end placed under the surface of mercury in an open vessel without allowing any mercury to escape from the tube while inverting it, the column of mercury in the tube will remain standing 29.9 inches high. The pressure of the atmosphere on the surface of the mercury in the open vessel is 14.7 pounds per square inch, and this pressure holds the mercury up in the tube. In a longer tube filled with water and placed upright with the open end under the surface of water in an open vessel the column of water will stand 34.9 feet high owing to the same cause.

In pumping problems, the height of liquid is called the *head.* The pressure per square inch on the lower face of 1 cubic foot of pure water is $62.5 \div 144 = .434$ pound. The pressure per square inch at the foot of *any column of pure water of any cross-sectional area* is .434 multiplied by the head in feet. Conversely, the head

equals the pressure per square inch divided by .434 or multiplied by 2.3; or, expressed as formulas,

$$p = .434h \qquad (1)$$

$$h = 2.3\ p, \qquad (2)$$

in which p = pressure in pounds per square inch;
h = head, in feet.

55. The **velocity** of water in a pipe may be calculated by the formula

$$v = \frac{.408\,Q}{d^2},$$

in which v = velocity, in feet per second;
Q = rate of discharge, in gallons per minute;
d = interior diameter of pipe in inches.

For example, if 700 gallons per minute is discharged from a 4-inch pipe, the velocity of the liquid in the pipe is

$$v = \frac{.408 \times 700}{4 \times 4} = 17.85 \text{ feet per second}$$

Any one of the three quantities represented by letters in the foregoing formula can be found if the other two are known. For example, to carry 750 gallons per minute at a velocity of 8 feet per second, the size of pipe is calculated as follows:

$$8 = \frac{.408 \times 750}{d^2}$$

$$d = \sqrt{\frac{.408 \times 750}{8}} = \sqrt{38.25} = 6.18 \text{ inches, diameter}$$

In practice, a standard 6-inch pipe would probably be used in this case, making the velocity $v = \frac{.408 \times 750}{6 \times 6} = 8.5$ feet per second.

56. The **weight** of water in a pipe is 1.022 d^2 pounds per yard, or *the weight in pounds in each yard of pipe is approximately equal to the square of the diameter in inches.*

57. The **power** required to drive a pump can be calculated by the formula:

$$\text{H. P.} = \frac{Q\,h}{3{,}960\,e}$$

or, approximately,

$$\frac{Q\,h}{4{,}000\,e} = \frac{25\,Q\,h}{10^5\,e},$$

in which H. P. = horsepower;
Q = gallons per minute;
h = head, in feet;
e = efficiency of the pump expressed decimally.

For estimating purposes, the efficiencies of triplex plunger pumps may be assumed at .60 to .85; those of centrifugal pumps at .35 to .75; and those of rotary pumps at .60 to .80.

EXAMPLE.—Find the horsepower required to pump 700 gallons per minute against a head of 35 feet with a centrifugal pump operating at 60 per cent. efficiency.

SOLUTION.—By substituting values in the formula, it is found that

$$\text{H. P.} = \frac{25 \times 700 \times 35}{10^5 \times .6} = 10.2, \text{ approx.}$$

58. Head of Liquids.—In calculating the power required for pumping, *suction head*, *discharge head*, and *friction head* must be combined to give the total head. **Suction head** is the vertical distance from the lower level of the liquid to the pump center; **discharge head** is the vertical distance from the pump center to the upper level, and **friction head** is the vertical head equivalent to the loss of pressure due to movement of the liquid through the pipes. The suction head and the discharge head together is the *actual lift*, or *rise*, of liquid. Friction head depends on the square of the velocity in the pipe, the length of pipe, and the conditions affecting freedom of flow, as elbows, bends, valves, and roughness of pipe interior. To obtain low friction head, the pipe should be ample in size, the interior smooth, and the number of sharp turns and valves small.

59. Table V gives friction head per hundred feet at a single rate of flow in each pipe. The friction head in a pipe at any other rate of flow and for any length of pipe can be calculated from the values given in the table.

Let h_1 = friction head to be calculated at Q_1 gallons per minute;
l = length of pipe in hundred feet;
h = friction head at Q gallons per minute, both given in Table V.

Then,

$$h_1 = l\,h\,\frac{Q^2_1}{Q^2}$$

TABLE V

FRICTION HEAD OF WATER IN STRAIGHT CLEAN WROUGHT-IRON PIPE

Inside Diameter Inches (d)	Gallons per Minute (Q)	Friction Head per 100 Feet (h)	Inside Diameter Inches (d)	Gallons per Minute (Q)	Friction Head per 100 Feet (h)
$\frac{3}{4}$	10	29.900	10	1,600	1.822
1	20	28.290	12	2,000	1.150
$1\frac{1}{4}$	30	21.040	14	2,500	.835
$1\frac{1}{2}$	50	23.000	16	3,000	.619
2	100	21.750	18	4,000	.609
$2\frac{1}{2}$	150	16.100	20	5,000	.562
3	200	11.540	24	7,000	.443
4	300	6.220	30	10,000	.298
5	400	4.252	36	15,000	.269
6	600	3.289	42	18,000	.207
8	1,000	2.174	48	20,000	.120

For example, 400 gallons per minute in a straight, clean, wrought-iron pipe, 6 inches in diameter and 1,500 (15 hundred) feet long will cause a friction head

$$h_1 = 15 \times 3.289 \times \frac{400^2}{600^2} = 21.9 \text{ feet,}$$

3.289 being the value per hundred feet for 600 gallons per minute in a 6-inch pipe, as given in Table V.

60. **Fittings** can be calculated as additional straight pipe according to Table VI. Unless the fittings are reamed out

smooth after machining, the values given in this table should be multiplied by 2. For example, two elbows and two globe valves in a 6-inch pipe line are equivalent to $2 \times 26 + 2 \times 50 = 152$ feet

TABLE VI

FEET OF STRAIGHT PIPE EQUIVALENT TO PIPE FITTINGS

Style of Fitting	Size of Fitting, Inches									
	$\frac{3}{4}$	1	$1\frac{1}{4}$	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	4	5	6
Elbows	5	5	6	7	7	10	12	18	25	26
Return bends	10	10	12	14	14	20	24	36	50	60
Globe valves	6	6	7	8	8	12	24	30	40	50

of straight pipe, provided the fittings are reamed out smooth, or 304 feet if left rough. If these fittings are included in the pipe assumed in Art. **59**, the length should be increased to 1,652 or to 1,804, according to the conditions of the fittings, making l in the solution either 16.5 or 18 instead of 15.

FANS, BLOWERS, AND EXHAUSTERS

61. An important application for electric motors is to drive devices for moving air and gas. The volume, pressure, and velocity of delivery of the gases, as well as the construction of blowers and exhausters, vary so widely that the power required in any given case is better obtained from experiment or from the manufacturers of such devices. Any fan may be called a *blower* if it forces air or gas into a chamber or system and an *exhauster* if it withdraws air or gas.

62. A **centrifugal fan** has an axial intake and a radial, or tangential, delivery. A centrifugal blower usually receives from both sides, while an exhauster may receive from one side only, this inlet being connected with the system from which air or gas is taken. Centrifugal fans are used for a great variety of purposes to move large volumes at pressures of a few ounces,

as for heating and ventilating, mechanical draft, removing dust, and poisonous gases, handling light materials, as grain and flour, etc. Restricting the inlet or outlet of these fans reduces the power required, provided the speed remains constant.

63. A **disk fan** both receives and delivers axially, causing a current of air or gas in the direction of the shaft. Disk fans are used almost entirely for ventilation and may operate as blowers or exhausters. The quantity of air moved and its velocity, rather than pressure, are the important considerations. Restricting the inlet or outlet of a disk fan operating at constant speed increases the power required.

64. A **positive pressure blower** is a rotary pump for air or gas. It delivers a fixed quantity per revolution, regardless of the pressure, giving the name *positive*. These blowers are used to move illuminating gas, air for blast furnaces, and for all purposes requiring gas or air at pressures ranging from a few ounces up to several pounds. Restricting the inlet or outlet very greatly increases the power required; if the restriction of the outlet is too great, the driving power will fail or some part of the system will burst on account of excessive pressure.

PERIODIC SERVICE

65. Motor ratings for service of a periodic nature, or a continually recurring cycle of operations, can be selected by the **root-mean-square (R.M.S.) method.** This method is based on the fact that heating in a motor is proportional to the square of the load and to the duration of the load. The square of each load during a complete cycle is multiplied by its duration, and the sum of these products is divided by the sum of the periods during the cycle; the square root of the quotient thus obtained is the horsepower rating of the motor for the cycle and for the whole time during which the cycle is to be repeated.

For example, suppose a motor must develop 20 horsepower for 5 seconds, then 30 horsepower for 15 seconds, then 10 horsepower 15 seconds, completing the cycle by running idle for 25 seconds, this cycle being repeated continuously for 2 hours.

The motor selected must, of course, be capable of developing the maximum output required, namely 30 horsepower, but a motor rated at 30 horsepower for 2 hours' service is much too large. The correct 2-hour rating is determined as follows:

$$
\begin{array}{rr}
20^2\times 5= & 2000 \\
30^2\times 15= & 13500 \\
10^2\times 15= & 1500 \\
0^2\times 25= & 0 \\
\hline
60\ ) & 17000 \\
\hline
 & 283.33+
\end{array}
$$

$\sqrt{283.33}=16.83$, approximately.

A motor rated at 17 to 20 horsepower for 2 hours will probably answer the requirement, provided it is capable of developing 30 horsepower for 15 seconds in order to cover the maximum requirement.

66. A good example of periodic service is operating a shovel for unloading ore from a vessel. A large clam-shell bucket is closed in the ore, hoisted, the trolley, or car carrying the hoist, is run in over the dumping place, the bucket opened, the trolley run out again, and the bucket lowered into the ore to begin another cycle, these cycles to be repeated continuously for 5 hours. One motor operates the bucket and another the trolley. Assuming a set of conditions, the rating of the motor for the bucket can be determined as follows:

Assumed Conditions			Solution	
Closing bucket	50 H. P.	8 sec...	$50^2\times 8=$	20,000
Hoisting	120 H. P.	10 sec...	$120^2\times 10=$	144,000
Trolley in	0 H. P.	10 sec...	$0^2\times 10=$	0
Opening bucket	20 P. H.	8 sec...	$20^2\times 8=$	3,200
Trolley out	0 H. P.	10 sec...	$0^2\times 10=$	0
Lowering and braking...	50 H. P.	9 sec...	$50^2\times 9=$	22,500
			55	189,700

$\sqrt{189{,}700\div 55}=\sqrt{3{,}450}=59$ horsepower, nearly. The motor must be capable of developing this output under the assumed conditions for 5 hours and also a maximum output of 120 horsepower for 10 seconds.

STORAGE BATTERIES

INTRODUCTION

DEFINITIONS

1. Strictly, the contact surface across which electricity flows from a solid to a fluid is an **electrode.** Usually, however, the term *electrode* is applied to the solid itself. An electrode from which electricity flows into a fluid is an **anode,** or *positive electrode;* an electrode into which electricity flows from a fluid is a **cathode,** or *negative electrode.* A conducting liquid is an **electrolyte.**

2. A **primary cell** consists of two unlike electrodes immersed in an electrolyte, whereby an electromotive force is developed between the electrodes, and an electric current is set up when the electrodes are connected by an external conducting circuit. The direction of this current is from the anode to the cathode in the cell, and from the cathode to the anode in the external circuit; therefore, the positive terminal of a cell is connected to the cathode, or negative electrode, and the negative terminal to the anode, or positive electrode. This point should be remembered. The flow of electricity is accompanied by chemical changes, or reactions, within the cell; these alter the chemical composition of the electrodes and, usually, that of the electrolyte also. The quantity of material altered by the chemical reactions is proportional to the quantity of electricity, in ampere-hours, that flows through the circuit. When any of the materials entering

into the chemical reactions of a primary cell has been entirely altered, the cell is exhausted, or fully *discharged*.

3. The **storage cell, secondary cell,** or **accumulator,** as it is variously called, is fundamentally the same as a primary cell, but differs in that when discharged, either wholly or partly, the storage cell can be restored to its original state, or *charged*, by passing current through it for a sufficient length of time in the reverse direction. The material of the electrodes that undergoes chemical changes during charge and discharge, called the *active material*, is generally supported on the surface or in the openings, or pockets, of a conducting framework, called a *grid*. The grid with its active material is called a *plate*. Each electrode in a storage cell consists of a plate or of a group of plates connected in parallel. The plates of the positive electrode alternate with those of the negative, in order to provide the shortest path for the current through the electrolyte.

Two types of commercial storage cell are in use: the *lead-sulphuric-acid cell*, sometimes called, simply, the *lead cell*, and the *nickel-iron-alkaline cell*, known also as the *nickel-iron*, or *Edison, cell*. The names are derived from the chemical natures of the electrodes and electrolytes.

THEORY OF COMMERCIAL STORAGE CELLS

4. In the **lead-sulphuric-acid cell,** the grids, both positive and negative, are of lead or of lead-antimony alloy. The active material of the positive plate when the cell is fully charged is lead peroxide, a chemical compound of lead and oxygen. The active material of the fully charged negative plate is metallic lead in a spongy, porous state. The electrolyte is a solution of sulphuric acid, formed by mixing 1 part of pure concentrated acid with 2.5 parts, by weight (4.5 parts by volume), of distilled water. The specific gravity of the electrolyte—that is, the ratio of the weight of a given volume to that of an equal volume of water—is about 1.2.

The lead and the oxygen in lead peroxide are chemically combined into a substance from which neither can be separated except by a chemical process. The lead peroxide undergoes such a process during a discharge of the cell; half of the oxygen is transferred from the positive to the negative plate, producing lead monoxide, another chemical compound of lead and oxygen, on each plate. At the same time, the sulphuric acid is decomposed into water and a gas called sulphur trioxide; this gas combines with the lead monoxide, forming lead sulphate on each plate. The active material on each plate of a fully discharged lead cell is therefore lead sulphate; and the electrolyte has become weakened because of the presence of additional water formed by the decomposition of some of the sulphuric acid. Not all the sulphuric acid disappears from the solution, because, originally, more than enough acid was added to convert all the active material on the plates of the fully charged cell into lead sulphate. The excess of acid is necessary because pure water alone is a non-conductor.

During charge, the reactions are reversed: the acid is restored to the electrolyte; the active material of the positive plate is oxidized to lead peroxide, and that of the negative plate is reduced to spongy lead; and the chemical conditions of a fully charged cell are gradually reestablished.

It will be noted that the specific gravity (strength) of the electrolyte decreases during discharge and increases during charge, thereby furnishing an indication of the state of discharge of the cell.

5. In the fully charged **nickel-iron cell,** the active material of the positive plate is nickel peroxide, and that of the negative plate is finely divided metallic iron. The electrolyte is a dilute solution of potassium hydroxide, or caustic potash. A small quantity of lithium hydroxide is added to the electrolyte to improve the capacity of the cell.

During discharge, part of the oxygen of the nickel peroxide is dissociated and transferred to the negative plate, where it combines with the iron to form ferrous (iron) oxide; but the composition of the electrolyte remains unchanged. Unlike

the electrolyte of the lead cell, the potassium hydroxide serves merely as a carrier of oxygen from one electrode to the other. When the cell is fully discharged, the active material of the positive plate is nickel oxide and that of the negative plate, ferrous oxide.

LEAD CELL

CONSTRUCTION OF THE LEAD CELL

FUNDAMENTAL TYPES OF PLATES

6. Two fundamental, or general, types of plates have been developed for use in the lead cell; the *Planté*, or formed, plate, and the *Faure*, or pasted, plate.

7. The **Planté plate,** so called after its inventor, Gaston Planté, consists of a sheet or a grid of pure lead, usually ribbed or corrugated in order to increase the superficial area, upon the surface of which the active material is formed out of the metal of the plate by an electrolytic process. The original Planté process consisted in immersing the positive and negative plates in a bath of dilute sulphuric acid, passing current through the cell for a number of hours, then reversing the direction of current for a similar period, and repeating this cycle many times until sufficient active material was formed on the plate surfaces to give the desired capacity. This process, called *forming*, or *formation*, was too slow and expensive to be commercial. Later, it was found that by the addition of a small quantity of nitric acid to the electrolyte the forming process could be materially accelerated, and could be completed for positive plates without reversal. Modern negative Planté plates are produced by reversing positives; that is, by immersing them in an electrolyte of dilute sulphuric acid opposite dummy electrodes, and passing current through the electrolyte from the dummies to the plates until all the peroxide of lead in the plates is reduced to pure lead sponge.

8. The **Faure plate,** invented at practically the same time by Faure in France and by Brush in the United States, consists of a grid provided with ribs, openings, or pockets, to which is applied the active material in the form of a paste consisting of red lead for the positive plate and of litharge for the negative. After the paste has set, the red lead of the positives is changed to lead peroxide and the litharge of the negatives to pure lead sponge by passing current through them in the proper direction in the forming bath of dilute sulphuric acid.

9. Relative Merits of Planté and Faure Plates.—The Planté plate is heavier, bulkier, and more costly than the Faure plate of the same capacity. The positive Planté plate is more durable than the ordinary Faure positive, but the durability of the two types of negatives is more nearly the same, especially if the same weight of material is used in each. The pasted positive is therefore used in portable cells, where minimum weight and space are of more importance than durability, and in cells for standby or emergency service, where but few charges and discharges are required per annum; the formed positive is used in stationary batteries in service requiring a comparatively large amount of work per annum, making durability of more importance. The negative Planté plate is standard with some manufacturers for stationary and car-lighting cells; it has the disadvantage that its capacity diminishes with use, owing to the tendency of the pure lead sponge to contract, harden, and lose its porosity. This tendency is counteracted in the Faure plate by the admixture of certain inert materials. Processes called *permanizing* have also been developed and patented for maintaining the capacity of the Planté negative. One such process consists in dipping the finished plate into a strong solution of sugar, and then carbonizing the sugar in the pores of the plate.

COMMERCIAL TYPES OF LEAD PLATES

10. The **Manchester positive plate,** details of which are shown in Fig. 1 (*a*), consists of a cast grid *A* of lead-antimony alloy perforated by circular openings, into which

rosettes, or buttons, *B* are forced by hydraulic pressure. Each button is formed by coiling into a spiral a strip of pure lead corrugated crosswise on one side, as shown in (*b*). When the buttons are in place, the corrugations are transverse to the plate and form the surfaces upon which the active material, lead peroxide, is formed by the accelerated Planté process.

The antimony in the grid renders it harder, stronger, and more rigid than one of pure lead, and also prevents electrolytic

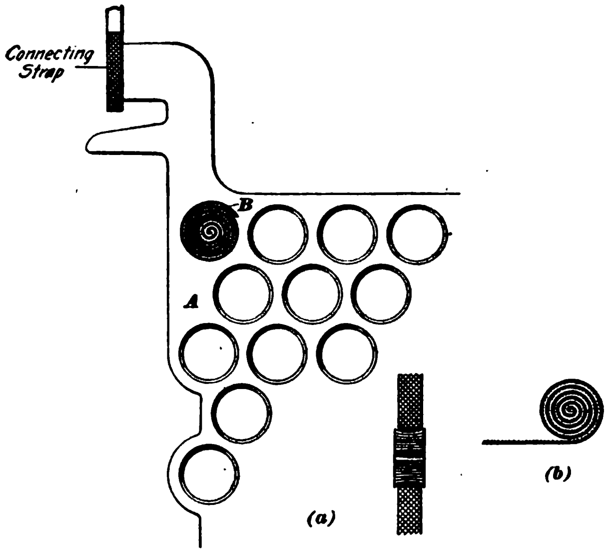


Fig. 1

corrosion, or formation, so that the grid remains intact throughout the life of the plate.

11. The **Tudor positive plate,** Fig. 2, consists of a pure cast-lead grid with both horizontal and vertical ribs, the openings between which extend entirely through the plate. The active material, lead peroxide, is formed in these openings on the transverse surfaces of the ribs by the accelerated Planté process. It is claimed that the absence of a central web, by permitting through-and-through circulation of electrolyte and, especially, by rendering the entire active material accessible

from either side of the plate, prevents the effect of unequal work on the two sides and makes the plate less subject to *buckling*, or distortion, than the soft-lead plates having central webs.

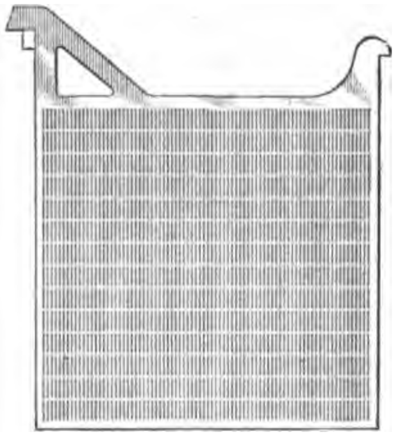


FIG. 2

12. The **box negative,** Fig. 3, has a grid of vertical and horizontal ribs of antimony-lead alloy forming pockets about 1 inch square. The active material, lead sponge, is retained in these pockets by perforated lead sheets. The grid is of the *split type*, originally cast in halves, the perforated sheet lead being placed in the mold before casting. After the active material is placed in the pockets, the two parts are riveted together and also lead-burned (process described later) together at the lugs. The box negative is used with the Manchester or Tudor positive in all but the smaller sizes of cells.

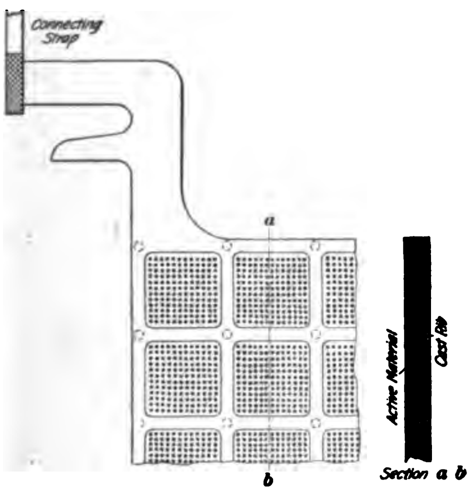


FIG. 3

13. The **shelf negative,** Fig. 4, is a pasted plate with a grid having main vertical ribs connected by short horizontal ribs, or shelves, between which is applied the active material. This type of negative is used in cells having plates 6 inches square or smaller.

14. The **Gould positive plate,** Fig. 5, has a pure lead grid made from a rolled-lead slab, or blank, upon the surface of which are developed closely spaced vertical leaves, or fins, by a spinning process. The process consists in passing the blank back and forth between two shafts bearing a series of steel disks spaced by intermediate washers of smaller diameter. The disks are forced into the blank while the shafts are rotated at high speed, the lead being thus spun, or forced, into the spaces between the hard-steel disks to form the leaves of the plate. The active lead peroxide is formed by the Planté process upon the surfaces of the leaves. The plate has a central web, and is also stiffened by horizontal and vertical ribs where the blank has not been reached by the rotating disks. A vertical section of part of a plate is shown in Fig. 6.

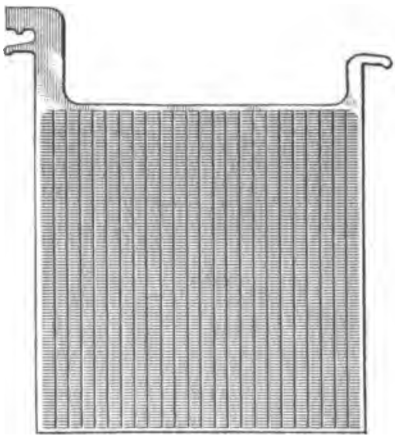


FIG. 4

The Gould negative plate is made in the same way as the positive, the peroxide being then reduced electrolytically to lead sponge.

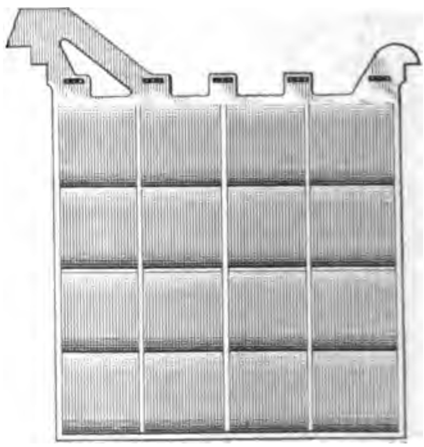


FIG. 5

15. The **Willard positive plate,** Fig. 7, has a pure lead grid made from a solid rolled-lead blank, upon the surface of which leaves are developed by a cutting tool,

or plow, that cuts each leaf at an angle with the surface and turns it up without removing any of the metal. The leaves are tapered in section, being thicker at the base, and extend vertically from the top of the plate to the bottom, no ribs of undeveloped surface being left by the tool. The central web is heavier at the top of the plate than at the bottom. The active peroxide is formed on the surfaces of the leaves by the Planté process.

The Willard negative plate is practically the same in structure as the positive.

Fig. 6

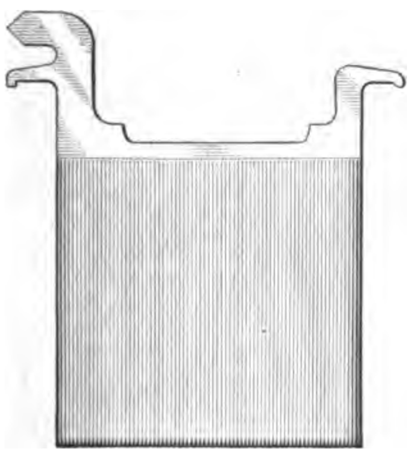


Fig. 7

Fig. 8

16. The **Exide plates,** positive and negative, are of the Faure type. As shown in Fig. 8, the grid consists of a series of vertical ribs connected by horizontal bars. The latter have a thickness less than that of the plate and are staggered as in Fig. 9, which shows a transverse vertical section of part of a plate. This design gives a large proportion of active material relative to the weight of the grid, tending to raise the output per unit weight of plate. This type of plate is recommended by the manufacturers for electric vehicles and for emergency reserve in connection with central lighting stations.

17. The **Diamond grid,** Fig. 10, has diagonal ribs staggered on opposite sides and connected by vertical ribs. The active material is pasted into this framework. This type of plate is claimed to be very rugged and free from buckling, and is used principally for electric vehicles.

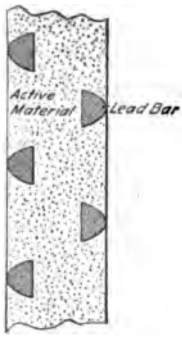


FIG. 9

18. The **Iron-Clad Exide positive plate,** Fig. 11, consists of a series of hard-rubber tubes arranged vertically in a frame of antimony-lead alloy. Each tube is filled with active material around a conducting core of the alloy integral with the frame. The tube is slotted horizontally throughout its length to provide access to the active material by the electrolyte. This method of confining the active material in permanent contact with the core makes a very durable plate.

The Exide negative plate is used with Iron-Clad positive.

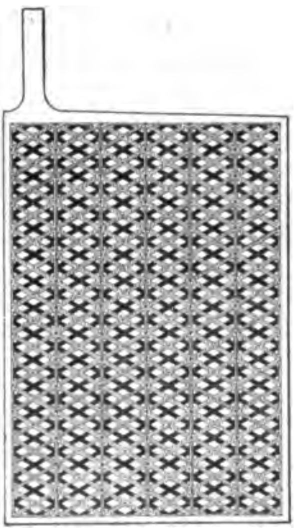


FIG. 10

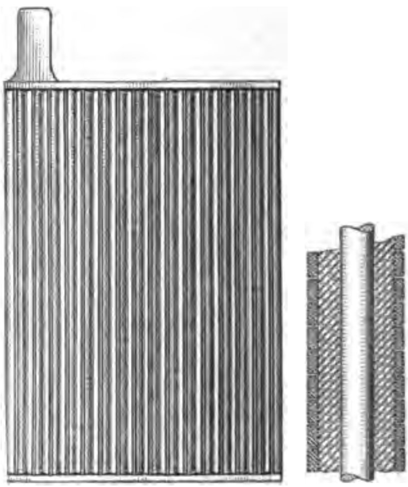


FIG. 11

19. **Plate Thickness.**—Pasted plates for electric vehicles and similar service are made in various thicknesses, depending

on the conditions of service for which they are to be used. Within certain limits, a given weight of lead if made into many thin plates will give more capacity than if made into a few thick plates. The thin plates are more expensive per pound to manufacture, and, if used to their full capacity on each discharge, they have a shorter life per pound of lead than the thick plates. It is claimed that by using regularly only a part of the full capacity, the thin plate will give a greater life, in ampere-hours, than the thicker plate. Different manufacturers are not wholly agreed as to the most economical thickness of plate to use for given conditions.

COMPONENT PARTS OF THE LEAD CELL

20. The component parts of the lead cell are the *element*, comprising the *positive-plate group* and the *negative group*,

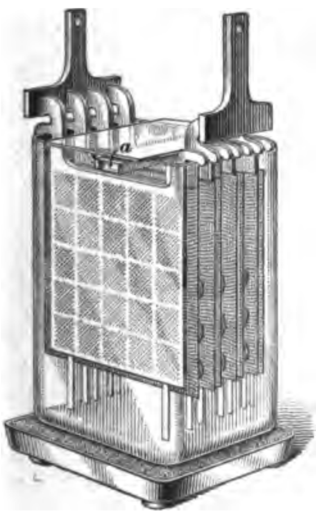


FIG. 12

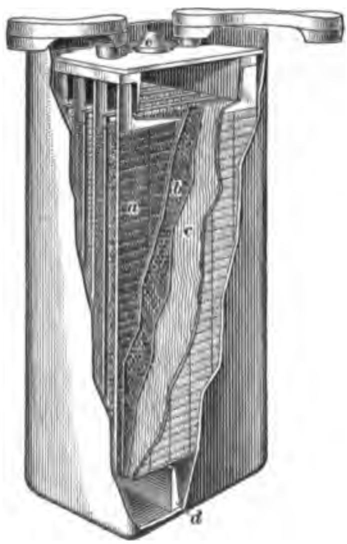


FIG. 13

including connecting straps, or bus-bars, and the *separators;* the *plate supports* (in lead-lined tanks); the *separator hold-*

downs; the *container*, consisting of a glass or a rubber jar or a lead-lined wooden tank; the *electrolyte;* the *cover;* and the *insulating cell support.*

Three types of lead cells are shown in Figs. 12, 13, and 14, the first with a glass container, the second with a rubber-jar container, and the third with a lead-lined wooden-tank container. In Fig. 13 part of the cell is shown cut away in order to display the arrangement of the interior.

21. Grouping.—In order to obtain the desired ampere-hour capacity, the necessary number of plates, positive and negative, are grouped in each cell, all the positive plates being connected to one terminal and the negatives to the opposite terminal. Except in the two-plate, or couple, type of cell (described later), the outside plates of an element are always negative, making one more negative plate than positive; all the positive plates are thus worked as nearly equal as possible from both sides, equalizing expansions and contractions of the active material and minimizing the tendency to buckle. The negative plate is not subject to this tendency.

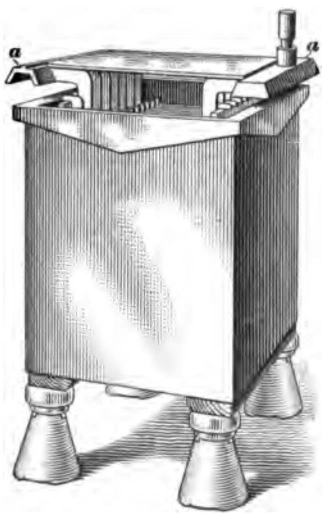
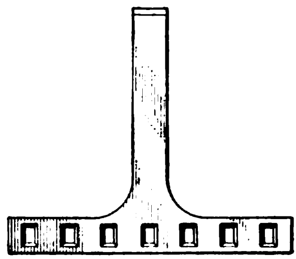


FIG. 14

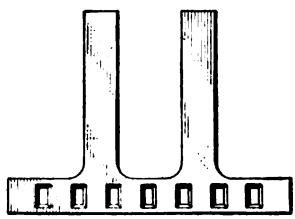
In assembling the plates into positive and negative groups for stationary cells, two types of cell terminal and intercell connection, **T** *straps* and *bus-bars*, are standard. For cells of the smaller capacities in glass jars, up to and including fifteen plates $10\frac{1}{2}$ in. $\times$ $10\frac{1}{2}$ in., the **T** strap, Fig. 15 (*a*), is employed. The lugs on the plates are inserted into the rectangular openings and secured by lead burning. Two straps are shown in place in Fig. 12. Connections between adjacent cells are made by bolting the vertical connecting straps together with brass bolts provided with lead-covered nuts. When, as

for very high rate discharge, low connection resistance is important, the connecting straps may be lead-burned together instead of using the bolt connectors or in addition to them. For cells containing nine or more plates 10½ in. × 10½ in., the double **T**, Fig. 15 (*b*), is commonly used. When either kind of **T** strap is used, plates are assembled into groups at the factory.

Plates in lead-lined tanks, as well as 10½″ × 10½″ plates in extra-heavy glass jars, are assembled by lead-burning the positive-plate lugs of one cell and the negative-plate lugs of the adjacent cell to a common bus-bar *a*, Fig. 14, between the cells. At points in the battery where current is to be taken from the series of cells, as at the ends of rows or between adjacent regulating, or *end*, cells (cells arranged to be cut into or out of circuit, as described later), the bus-bars are reinforced by embedding a copper bar in the lead, as shown in Fig. 16 (*a*) for cells of small capacity and in (*b*) for cells of large capacity. The copper reinforcement improves the conductance and insures uniform distribution to all the plates in the cell. Where bus-bars are used, plates are shipped separately and are lead-burned to bus-bars when the cells are set up.



(*a*)



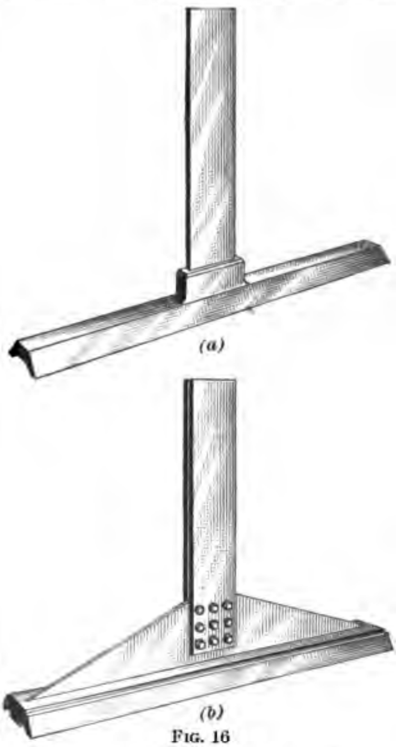
(*b*)

Fig. 15

In cells of small capacity, only two plates, one positive and one negative, are sometimes used. These are called *two-plate*, or *couple-type*, cells. The positive plate of one cell and the negative plate of the adjacent cell are permanently lead-burned to a **U**-shaped connecting strap that supports the plates from the edges of the jars, as shown in Fig. 17, which illustrates a ten-cell battery.

A type of connector for electric vehicle cells is shown in Fig. 13.

22. Separators.—The use of vertical glass tubes for separating adjacent plates in stationary storage cells is practically obsolete; diaphragm separators of thin wood, Fig. 18, are now used in all stationary cells and in nearly all portable cells. In stationary cells, these diaphragms are supported in the slots of vertical dowels, which also serve to space the plates. In some cases, the dowels extend to the bottom of the cell, as in Figs. 12 and 18 (*a*); in other cases, they extend to only the bottom of the plate, as in Fig. 18 (*b*). In the latter case, the middle dowel—or each dowel if only two are used—hangs on a hard-rubber pin that passes through the dowel and rests on the tops of adjacent plates. The latter construction is preferable, as it leaves the space beneath the plates free for the removal of sediment. In stationary cells, wooden separators are prevented from floating by blocks of glass *a*, Fig. 12, called *separator hold-downs*, resting on the tops of the plates.


(*a*)

(*b*)

Fig. 16

In portable cells, vehicle cells, automobile ignition cells, and in large central-station batteries for emergency service, where plate spacing is reduced to minimize space and weight, the dowels are omitted and the wooden separators are grooved on one or both sides to provide for circulation of the electrolyte. In nearly all such cases, except central-station standby batteries, perforated sheets of hard rubber are inserted between the wooden separators and the adjacent positive plates, as

shown in Fig. 13, in which *a* is a positive plate; *b*, a rubber separator; and *c*, a wooden separator.

Wooden separators require a preliminary treatment for removal of organic acids, and must be kept constantly wet until installed in the cells.

Where the cells are subjected to considerable motion, as in train lighting and yacht lighting, but the plates are not

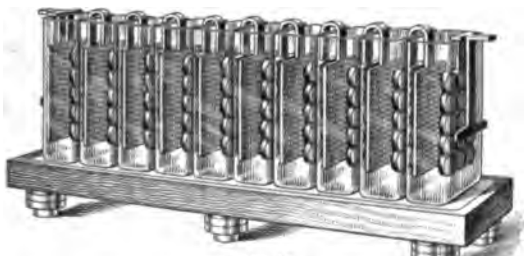
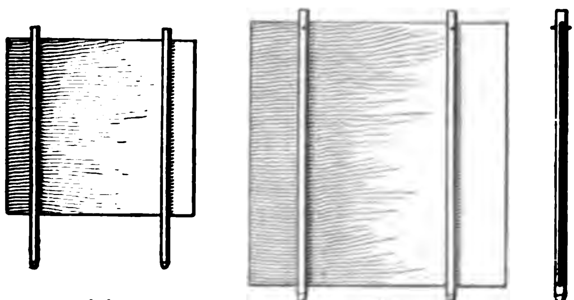


FIG. 17

close enough together to hold the separators firmly in position, sheet-rubber separators are used alone. In cells for automobile ignition, starting, and lighting systems, wooden sepa-



(a) (b)

FIG. 18

rators are sometimes used alone, reducing the cost of the cells at a sacrifice of durability.

23. Plate Supports.—In all rubber jars, the plates rest on ribs *d*, Fig. 13, on the bottom of the jar. In lead-lined tanks for train lighting, the plates are set on porcelain rests of inverted V section on the bottom of the tank. In all

stationary cells with glass jars or wooden tanks, the plates are provided, on each side near the top, with lugs that rest on the edges of the glass jars, as in Fig. 12, or on vertical sheets of glass in lead-lined tanks.

24. Electrolyte.—The specific gravity of electrolyte for commercial cells varies from 1.200 to 1.300. The lower density is used in stationary cells, where there is space for an ample supply of electrolyte. The higher densities are used in portable cells, where the volume of electrolyte is restricted, in order to furnish a sufficient quantity of acid to combine with the active material of the plates and still maintain satisfactory density at the end of discharge.

Electrolyte must be free from certain impurities, such as chlorides, nitrates, iron, copper, arsenic, platinum. Some impurities, such as lead and calcium, are not injurious.

In referring to the density of electrolyte, the decimal point is sometimes omitted; electrolyte of 1.200 specific gravity, for instance, is called *1200 acid*.

25. Covers.—Glass covers are generally used on stationary cells with lead-lined tanks or glass jars, as shown in Figs. 12 and 14. They serve to reduce the evaporation from the cells, and the spray that arises from the electrolyte toward the end of a charge condenses on the under surface of the cover and drops back into the cell. Cells in rubber jars, Fig. 13, are furnished with hard-rubber covers, usually sealed around the edges and around the projecting terminals with a compound of asphalt composition designed to remain plastic at low temperatures without becoming too soft when warm. The rubber cover is usually provided with a hole for filling that can be plugged with a soft-rubber stopper *e*, Fig. 13, having a small vent hole in the center.

26. Insulating Supports.—Cells in glass jars are supported on shallow trays of wood or glass filled with sand to distribute the weight of the cell uniformly over the bottom of the jar. Glass trays are preferable on account of durability, and can be obtained for all but the very largest sizes of cells.

Glass trays, Fig. 12, have glass feet; wooden trays, Fig. 17, rest on glass insulators of the petticoat type.

The most satisfactory support for cells with lead-lined tanks is the *oil insulator*, Fig. 19. The glass body *a*, in the shape of an annular trough, is half filled with oil and then covered with a lead cap *b*. The upper outer edge of the glass trough is provided with a projecting lip and the lower edge of the lead cap is beaded internally to prevent water or acid from splashing into the trough. The glass trough rests on an earthenware pedestal *c*. Four of these insulators support the cell shown in Fig. 14.

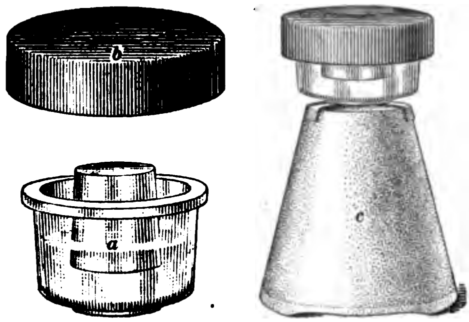


FIG. 19

Porcelain insulators, even though thoroughly glazed, have been found unsatisfactory for supporting lead-lined tanks, as the glazing eventually breaks down. Glass insulators in double tier, which superseded porcelain, would in many cases become coated with a film of acid and dirt, providing a path for leakage current that would in time puncture the lead lining of the tank by electrolytic action.

CHARACTERISTICS OF THE LEAD CELL

CAPACITY

27. The **capacity** of a storage cell, expressed in ampere-hours, is the product of the rate of discharge in amperes by the number of hours the cell will maintain that rate on full charge. The ampere-hour capacity varies with the rate of discharge, being less at high rates than at low rates. The capacity of a standard stationary cell is based on the *normal*,

or *8-hour, rate* of discharge. Trade catalogs give the 5-hour rate as 1.4 times the normal, the 3-hour rate as twice normal, and the 1-hour rate as four times normal. On this basis, the capacity of a cell at the 1-hour rate is just one-half its capacity at the 8-hour rate. On test, a cell that will give 8 hours at normal rate will usually give somewhat more than 1 hour at four times normal; and a cell that will give just 1 hour at the catalog 1-hour rate will give only about 7 hours at normal rate. However, if a cell having the full 8-hour capacity at normal rate of discharge is worked regularly at the 1-hour

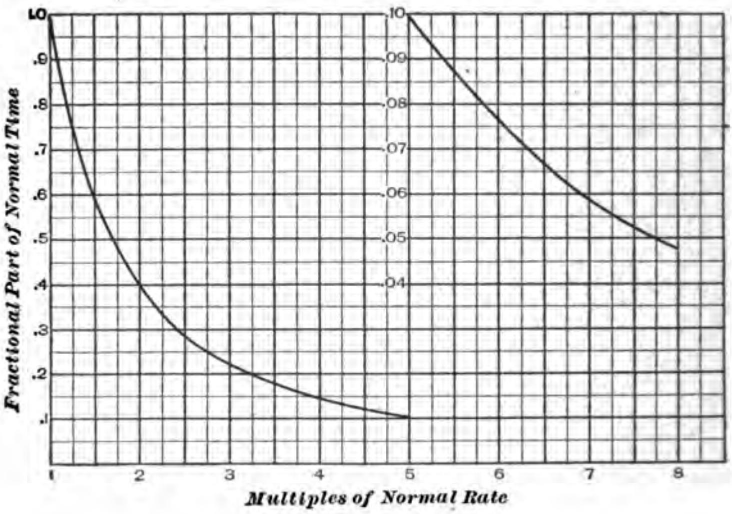


FIG. 20

rate, its capacity will fall off until it settles down to 1 hour at the 1-hour rate. Conversely, a cell with a capacity of just 1 hour at the 1-hour rate and 7 hours at normal rate, if worked regularly at the latter rate will increase in capacity eventually to about 8 hours, instead of 7, at the normal rate. The ratings in trade catalogs are based on these facts.

Capacities of vehicle cells are usually stated at the 4-, $4\frac{1}{2}$-, or 5-hour rate. The capacities of batteries for gasoline-engine ignition are usually given in ampere-hours at the service rate, which is generally based on the 20-hour rate of discharge.

28. In Fig. 20 is a curve that shows the relation between discharge rate and time for a standard stationary cell. The rates are given in multiples of normal rate, and the corresponding times in fractional parts of the normal time. The curve is drawn in two parts, to different scales, in order to make the small values of fractional parts of time more readable.

The relations shown by the curve apply to continuous and constant rates of discharge only. If the discharge is intermittent, the available capacity will be increased to an extent depending on the total elapsed time over which the intermittent discharges are distributed. Thus, if brief discharges at the 1-hour rate are distributed with approximate uniformity over a period of 8 hours, nearly full 8-hour capacity will be obtained.

VOLTAGE

29. The total electromotive force, in volts, that is generated within a storage cell by the chemical action and that is effective in producing current through the total resistance of the entire circuit, including the internal resistance of the cell, is the **internal, or true, voltage** of the cell. The **external voltage** of a cell is that which can be measured by connecting a voltmeter across the cell terminals; it is equal to the internal voltage minus the drop through the internal resistance. If the cell is delivering no current, the internal and external voltages are equal.

30. The **open-circuit voltage** of the lead storage cell is from 2.05 to 2.08; and if a cell is allowed to remain on open circuit a sufficient length of time, its external voltage will settle to something between these values, whether the cell is fully charged or practically discharged. The open-circuit voltage of a cell is, therefore, no guide to the state of charge.

The so-called **floating voltage** of a cell is the voltage that must be maintained across its terminals to keep it in a constant state, neither charging nor discharging. The value of the floating voltage, from 2.08 to 2.1, must be slightly higher than the open-circuit voltage in order to compensate for

local action, or so-called *self-discharge*, which is due to electrochemical action in small circuits within the plates themselves.

31. Discharging Voltage.—During discharge the external voltage of a cell drops below the open-circuit voltage by an amount that varies with the rate and duration of the discharge. This drop in voltage is due to two causes. The drop that takes place instantly on starting the discharge is due to the internal resistance of the cell and is directly proportional to the current; the additional drop, which occurs

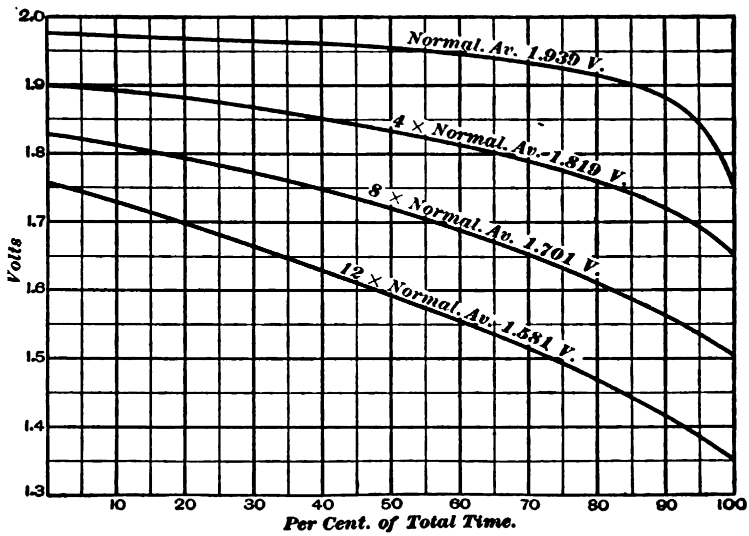


FIG. 21

slowly at first and then more rapidly as the discharge proceeds, is due to so-called *polarization*, which is caused largely, if not wholly, by the weakening of the acid in the pores of the plates. The final voltage at the end of discharge at the normal rate is 1.75; at the 1-hour rate, 1.6 to 1.65—voltage readings to be taken while the cell is still delivering current. Fig. 21 shows discharge voltages at several different rates for cells with plates $10\frac{1}{2}$ in. × 11 in., Tudor positive and box negative, and Fig. 22, for cells with plates $15\frac{5}{8}$ inches square, Tudor positive and box negative. The rate of discharge, in terms

of a multiple of normal, and the average voltage for the discharge are given beside each curve. The instantaneous drop

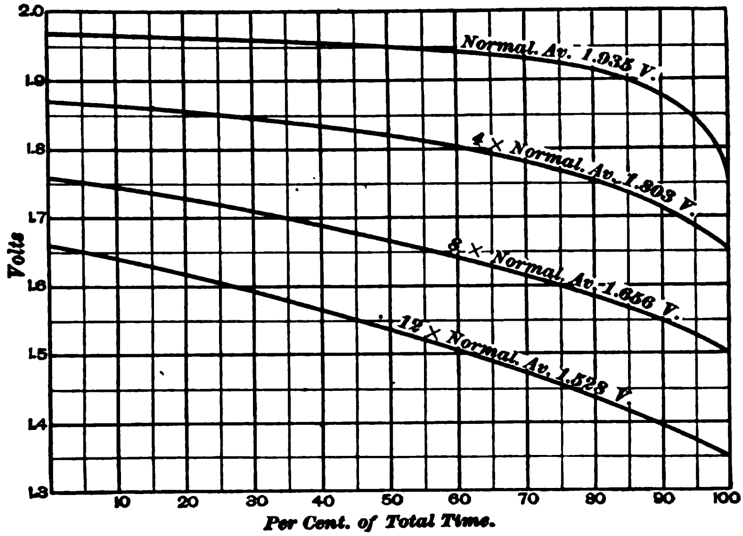


FIG. 22

at the beginning of discharge is not shown in Figs. 21 and 22.

32. Charging Voltage.—When charging current is passed through a cell, the instantaneous rise of voltage above

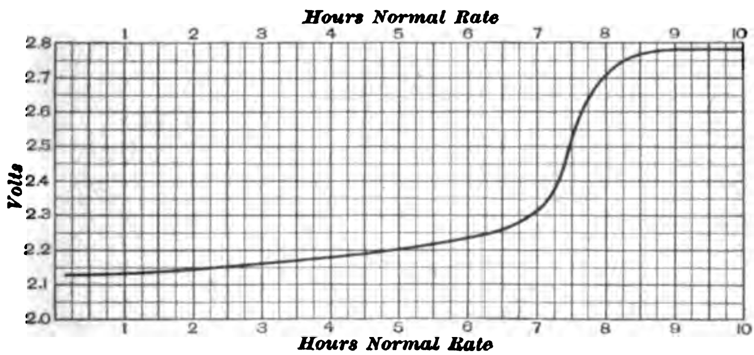


FIG. 23

the open-circuit value is due to internal resistance, and the subsequent gradual rise is due to polarization caused by the

strengthening of the acid in the pores of the plates. Toward the end of a complete charge, a further rapid rise in voltage occurs, due to the collection of bubbles of oxygen and hydrogen in the pores of the positive and negative plates, respectively—the result of the decomposition of the electrolyte, which occurs when practically all the active material in the plates has been brought to the state of full charge. The final voltage at the end of a charge at normal rate, with the charging current still flowing, is from 2.6 to 2.8. This applies to comparatively new cells; those which have been in service for several years may not exceed 2.5 or 2.4 volts at the end of charge. In Fig. 23 is shown a curve of charging voltage at normal rate. It will be noted that the voltage does not rise appreciably after the end of the regular charge at 8½ hours.

INTERNAL RESISTANCE

33. The internal resistance of a cell or a series of cells is best measured after discharging at constant rate long enough to obtain a steady voltage at the terminals, and then quickly interrupting the discharge and noting the instantaneous rise of voltage. This instantaneous rise divided by the value of the current at the instant of interruption gives the true internal resistance. Instead of completely interrupting the discharge, the current may be suddenly reduced or increased by a definite amount, and the internal resistance found by dividing the instantaneous change in voltage by the change in current. The internal resistance of standard stationary cells is such as to cause an instantaneous drop in voltage of 6 to 7 per cent. when subject to a momentary discharge equal to the 1-hour rate.

The polarization drop, which occurs within a few seconds after the discharge begins, may add from 20 to 30 per cent. to the internal resistance drop, and in many calculations may be treated as a true ohmic drop.

SPECIFIC GRAVITY OF ELECTROLYTE

34. As previously stated, the specific gravity of the electrolyte of a lead cell decreases during discharge, the initial specific gravity being restored on charge. In stationary cells, the maximum specific gravity is about 1.210, which drops to 1.170 or 1.180 at the end of a complete discharge. The range of specific gravity varies with the total amount of electrolyte in the cell as compared with the capacity of the plates. When this range is once determined, the state of charge of a cell can be ascertained at any time by observing the specific gravity, which varies in direct proportion to the ampere-hour capacity remaining in the cell.

In vehicle cells, the maximum specific gravity is about 1.275, and in automobile ignition cells, 1.300, with a minimum at the end of discharge of about 1.100 in both types.

TEMPERATURE

35. The foregoing data on lead cells are based on a cell temperature of 70° F.

The capacity of a lead cell decreases with reduction of temperature. At normal rate, the loss amounts to about six-tenths of 1 per cent. of the 70° capacity for each degree reduction in temperature. At higher rates, the percentage of loss is somewhat greater.

The internal resistance of a lead cell increases with reduction in temperature. At 0° F. the internal resistance is about double that at 70° F.

The specific gravity of the electrolyte varies also with temperature in the proportion of an increase of 1 point (.001) in specific gravity for every drop in temperature of 3 degrees (F). This correction must be applied and the observed specific gravity reduced to the equivalent at 70° F. before using it as a guide to the state of charge of the cell.

EFFICIENCY

36. The **ampere-hour efficiency** of a storage cell is the ratio of the discharge, in ampere-hours, to the charge, in ampere-hours, required to bring the cell back to the same state of charge. The ampere-hour efficiency can be reduced to almost any low value by excessive and unnecessary overcharge. Aside from this, the legitimate ampere-hour efficiency varies with a number of conditions: the age and condition of the plates, the temperature, the rate of charge, the elapsed time between charge and discharge, the ratio of the amount of discharge to the battery capacity, and the particular states of charge and discharge between which the battery is worked. Under average conditions, an ampere-hour efficiency of 90 per cent. can usually be obtained.

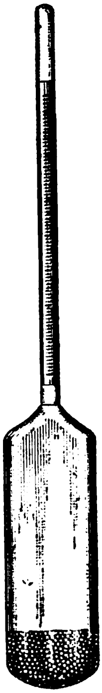


FIG. 24

The ampere-hour losses are due to two causes: local action, or so-called self-discharge, and gassing during charge. *Local action* may be caused by impurities in the plates or electrolyte or by local short-circuits, and the effect of these is increased at high temperature and by long standing; but under normal conditions this cause of low efficiency is almost negligible. *Gassing* is the term applied to the evolution of hydrogen and oxygen gases, due to the decomposition of the electrolyte when a charge has been continued to a point where very nearly all the active materials have been converted into lead sulphate. The effect of gassing can be reduced by reducing the charging rate as soon as gassing appears. Under ideal conditions, an ampere-hour efficiency of almost 100 per cent. may be realized.

37. The **watt-hour efficiency** of a storage cell is the ratio of the energy taken out of the battery to that put in, both measured in watt-hours. It is equal to the ampere-hour efficiency multiplied by the voltage efficiency, that is, by the

ratio of average voltage during discharge to average voltage during charge. The watt-hour efficiency, therefore, depends not only on the factors that affect the ampere-hour efficiency, but also on those which affect the voltages of charge and discharge. The voltage efficiency depends principally on the rate of charge and discharge, as well as on the size and type of plates, the cell temperature, and the range through which the battery is worked. The average voltage and resulting voltage efficiency can be obtained from the charge and discharge curves. Under test conditions, a watt-hour efficiency of 85 per cent. may be obtained with charge and discharge at normal rate, and even higher if the charging rate is tapered, or lowered toward the end, to avoid gassing and high final voltage.

Efficiency tests should include several cycles of charge and discharge, in order to reduce the effect of error in determining when the original state of charge has been restored.

CARE AND OPERATION OF LEAD BATTERIES

TESTING INSTRUMENTS AND APPARATUS

38. The **hydrometer,** one style of which is shown in Fig. 24, is used for measuring specific gravities of electrolytes; this instrument can be obtained with numbered scales ranging between 1,100 and 1,300. One or more hydrometers of the type illustrated can be kept floating in the electrolyte of a stationary battery. In vehicle and other portable cells, however, there is not enough space for inserting a hydrometer, and part of the electrolyte must be withdrawn with a syringe and removed to a test-tube or some vessel in which the hydrometer can be floated. A more convenient device is the **hydrometer syringe,** Fig. 25, consisting of a rubber bulb provided with a glass barrel containing the hydrometer. The electrolyte is drawn up into the barrel until the hydrometer floats, when the reading may be taken and the electrolyte returned to the cell.

In order to correct specific-gravity readings for variations of temperature, as well as to guard against excessive temperature in portable and vehicle cells during charge, a thermometer must be provided. Floating thermometers can be used in stationary cells.

In order to follow the operation of a large stationary battery intelligently, it is customary to select one cell as a pilot cell, the condition of which serves as a guide to that of the entire battery.

FIG. 25

39. In stationary batteries of considerable magnitude, such as are installed in connection with central power stations, **compensating and recording hydrometers** are usually employed. The compensating hydrometer is provided with an internal chamber filled with electrolyte and communicating with the external electrolyte in a pilot cell through a small outlet so curved as to provide a liquid seal. The expansion and contraction of the electrolyte in the chamber compensates for changes of temperature. This hydrometer is suspended from the arm of the recording device, which arm carries a pen that records the changes of specific gravity on a record sheet moved by clockwork. This instrument is provided with contacts for closing a circuit and giving a signal when the specific gravity reaches a certain maximum or minimum.

40. The record of a compensating hydrometer is a reliable indication of the state of charge of a battery only when the water lost from the pilot cell by evaporation and gassing is constantly replaced to the same level. This is accomplished by means of the **automatic pilot-cell filler,** Fig. 26, which consists of a bottle of pure water provided with a curved-tube outlet having a small hole at the lowest point of the tube, normally below the surface of the electrolyte. When the level of the electrolyte falls, a bubble of air passes through the hole into the bottle, thus releasing an equivalent volume of water.

41. A **low-reading voltmeter** is also an important instrument for reading the voltage of individual cells. The scale should have a range from 0 to 3 volts, divided into tenths. A **double-scale voltmeter** is still more convenient, the lower scale having a range of three volts, and the higher scale having a sufficient range to read the maximum voltage of the entire series of cells.

42. An **ampere-hour meter** is a very convenient instrument for indicating the state of charge of a battery and determining the proper amount of charge to be given. These instruments can be obtained with a dial scale and a pointer adjusted to make one revolution for a complete discharge and return toward the zero position during charge. If the pointer travels at the same rate for charge and discharge, it can be set ahead by 10 or 15 per cent. just before the charge begins, so that when it has returned to zero the desired amount of overcharge will have been given; or the instrument can in some cases be so adjusted that the pointer travels 10 or 15 per cent. slow during charge, requiring an excess charge of 10 or 15 per cent., in ampere-hours, to bring it back to zero. These ampere-hour meters are sometimes provided with a contact that trips a circuit-breaker in the charging circuit when the pointer has returned to zero, thus stopping the charge automatically. Such instruments are satisfactory where the rates of charge and discharge do not vary over too wide a range; they are reasonably accurate from 50 per cent.


FIG. 26

of overload down to 5 per cent. of rated capacity; but if any considerable proportion of the charge or discharge takes place at rates outside of the range of accuracy, the indications will be misleading.

OPERATION AND CARE

43. Assembling.—Special instructions are furnished by the manufacturers for assembling and connecting up the cells of a battery. The following are the more important precautions to be observed:

The positive and negative groups should first be assembled in the containers and connected up *before* the electrolyte is put in, the positive terminal of each cell being connected to the negative terminal of the adjacent cell. The wooden separators should be kept wet until they are placed in position in the cells, and the electrolyte should then be added before the separators are allowed to dry.

Electrolyte of the proper density for immediate use is usually furnished. If strong acid (oil of vitriol, or 1.800 specific-gravity acid) is obtained, it must be diluted with pure water before being poured into the cells. This diluting, or "breaking down," of strong acid must be done with great care, as a large amount of heat is developed during the operation. *Never add the water to the acid*, as this will produce dangerous sputtering. Add the acid to the water very slowly, especially when a glass vessel is used, to avoid cracking the glass with excessive heat, and stir constantly during the process. Allow the mixture to cool before putting it into the cells.

44. Polarity.—Before connecting a battery to the charging circuit, the polarity (positive or negative) of each of the two conductors of the charging circuit must be determined. If there is any doubt as to this, a simple test may be made by connecting two wires, one to each conductor of the supply circuit, with enough resistance in series to limit the current to about 1 ampere or less, and then dipping the two wires in a vessel of acidulated water or in water in which a small amount of common salt has been dissolved, keeping the ends

of the wires about an inch apart. The wire from which bubbles of gas are given off more freely is connected to the negative side of the circuit. The positive terminal of the battery must then be connected to the positive conductor of the circuit, and the negative terminal to the negative conductor. The positive terminal of a stationary battery may be distinguished by the dark-brown color of the plates to which it is connected, the negative terminal being connected to the slate-gray plates. The terminals of portable batteries, in which the cells are sealed, preventing inspection of the plates, are usually marked for polarity. If they are not marked, a voltmeter may be used or the test just described may be employed.

45. Initial Charge.—Immediately after assembling and as soon as possible after the electrolyte has been put into the cells, charging should be started and continued at the 8-hour rate, with as little interruption as possible, for a period of from 35 to 60 hours, depending on the type of plate. Special instructions are furnished by the manufacturers.

46. Regular Charge.—A regular charge is given to the battery as frequently as may be necessary to restore the energy taken out on discharge. This regular charge can be given at the normal rate throughout; but if it is necessary to hasten the charge, a considerably higher rate can be used at the beginning, provided the rate is reduced from time to time to prevent violent gassing and to keep the temperature of the cells below 110° F. The regular charge should be continued until the specific gravity of the pilot cell is from 3 to 5 points below the maximum reached on the preceding overcharge. All the cells should then be gassing moderately, but not so freely as at the end of overcharge.

When a battery has been completely discharged, the charge should be started as promptly as possible. Long standing in a discharged condition tends to produce in the plates a hard and crystalline form of lead sulphate that will reduce their capacity temporarily. This sulphate may not cause permanent injury, because it can be decomposed by a long overcharge at low rate.

47. Periodic Overcharge.—Once every week or two a battery should receive an overcharge, which consists in prolonging the regular charge at normal rate until the specific gravity of the pilot cell has reached a maximum and remains stationary for 1 hour, and all the cells are gassing freely. The object of this overcharge is to bring all the cells to a uniform, healthy condition.

48. Indication of a Complete Charge.—The most reliable indication of a complete charge in a lead cell is the fact that the voltage and the specific gravity have reached a maximum and become stationary for 15 minutes to ½ hour, the charging current being maintained constant. These final values of voltage and specific gravity are not always the same, the former varying with the temperature, the rate of charge, the type of plates, and the age of the battery, and the latter with the temperature, the height of electrolyte, and the amount of acid lost by spraying or combination with sediment in the bottom of the cells. The theoretical values of voltage and the specific gravity are not therefore a sure indication of complete charge.

An ampere-hour meter connected into the battery circuit, both during charge and discharge, is usually a very satisfactory guide in determining the proper amount of charge. In general, an excess of from 10 to 15 per cent. in charge over discharge, measured in ampere-hours, is desirable to keep the cells in good condition. (See Art. 42.)

Toward the end of the charge the cells will gas very freely, an indication, in a healthy cell, that the charge is approaching completion. Plates that are badly sulphated (see Art. 46) will gas freely long before the charge should be stopped.

While charging vehicle or other portable cells in sealed rubber jars, the soft-rubber stoppers in the covers should be removed and the cover of the battery box or compartment should be left open.

It should always be carefully borne in mind that the gases, oxygen and hydrogen, given off by a battery toward the end of charge form an explosive mixture. The battery room or

compartment should therefore be freely ventilated at such times, and the proximity of an exposed flame should be absolutely prevented.

49. Effect and Remedy of Short Circuit.—At the end of the charge preceding the overcharge, the specific gravity of the electrolyte in each cell should be read and recorded. If the specific gravity of any cell is markedly lower than that of the others, that cell should be examined for short circuits. Such a cell should be carefully inspected during the overcharge to note whether it gasses later or less freely than the others. If the short circuit has been removed, the overcharge will probably bring the cell back to normal condition. If the cell is very low as compared to the others, full capacity may not be completely restored until after the second overcharge. Sometimes the cell must be cut out of circuit and treated to a prolonged charge at normal rate separately

50. Discharging.—The only limit to the rate of discharge of a lead cell is the safe carrying capacity of the plate lugs and connections. Four or five times the 1-hour rate may be taken from a cell for a few minutes, and even higher rates momentarily if special high-capacity plate lugs are furnished. Excessive discharge, in ampere-hours, at low rate should be avoided as far as possible, and if such discharge should occur the cells should be recharged as soon as possible.

51. Filling Cells.—The electrolyte should be kept above the tops of the plates by filling the cells with pure water from time to time. Under normal conditions of temperature and ventilation, filling once a week is usually sufficient. Acid should never be added to the cells except by special instructions from the manufacturer. The acid in the electrolyte does not evaporate. A very small amount of acid may be carried off in spray during charge, but the greater part of this is retained by the covers, so that the loss from this cause is appreciable only after a year or two of service. A small amount of acid is also lost when sediment is removed from the cells.

In some cases, the local supply of water is sufficiently pure to use for filling the cells. Rainwater caught on a clean slate

or a shingle roof is usually satisfactory, provided the atmosphere is not contaminated with soot or other foreign particles. The roof should be allowed to flush off for a while before the water is collected for use in the battery. Battery manufacturers will usually make, without charge, the necessary tests to determine the purity of local water supply. A quart sample of water should be furnished for such test.

If the local supply of water is not sufficiently pure, distilled water can usually be purchased. A still is often installed for purification of the water required by a large battery.

Water for filling cells should be stored and handled in wooden, earthenware, or glass vessels; iron or other metal should be avoided.

The amount of evaporation varies with the temperature, atmospheric humidity, and character of ventilation. Under average conditions, the height of the electrolyte in the cells may be reduced from $\frac{1}{2}$ to $\frac{3}{4}$ inch per week. This depth, together with the number and dimensions of the cells, will give the quantity of water required per week for filling.

EXAMPLE.—The depth of electrolyte in a battery of 200 cells is reduced $\frac{1}{2}$ inch per week by evaporation. Each cell is $25\frac{1}{2}$ in. $\times$ 12 in., inside dimensions. How many gallons of water per week will be required to replace the loss by evaporation?

SOLUTION.—The amount of water lost by evaporation is $200 \times .5 \times 25.5 \times 12 = 30{,}600$ cu. in. One United States gallon contains 231 cu. in.; therefore, $30{,}600 \div 231 = 132.5$ gal., nearly, will be required. Ans.

52. Battery-Room Ventilation.—The battery room, or compartment, should be well ventilated, especially during charge, to prevent excessive rise of temperature, to remove acid spray before it collects on tanks, insulators, etc., and to prevent the accumulation of explosive gas mixtures. In small installations, good natural ventilation by doors and windows is satisfactory. For large batteries, artificial ventilation is frequently employed, preferably by exhausting the air at one end of the room near the top, allowing the fresh air to enter at the other end near the floor through numerous openings of large aggregate area.

53. Removal of Sediment.—In service, a certain amount of the active material of the plates is dislodged and falls to the bottoms of the cells. This sediment must be removed before it accumulates in sufficient quantity to touch the bottoms of the plates and short-circuit them.

Sediment can be removed from small cells by removing the element (being careful to press the plates together to retain the separators in position), pouring off the clear electrolyte, flushing out the sediment, replacing the element, and pouring back the clear electrolyte. Loss of electrolyte can be made up by adding fresh electrolyte of the same density. The work should be done on one cell at a time, and the element should remain exposed to the air no longer than absolutely necessary.

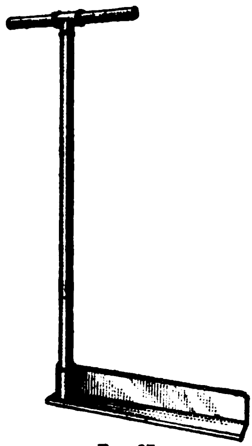


FIG. 27

If the cells are too large to be handled in the manner just mentioned, the sediment can be removed with a scoop of wood or aluminum of special design, Fig. 27, having a horizontal blade of L section with a vertical handle at one end. The scoop is inserted between the outer negative plate and the side of the jar, with the vertical edge of the blade against the side of the jar and the horizontal edge on the bottom, the handle rising at one corner. By using the handle as an axis, the blade is swept over the bottom of the jar under the plates through an angle of 180°, the handle being at the same time moved along the side of the jar until it is brought to the opposite corner, still in a vertical position. The blade is thus again brought against the side of the jar in reversed position with its vertical edge away from the jar wall. By holding the blade against the side of the jar, the scoop can be raised, bringing the sediment with it. Wooden scoops are used with glass jars, because they are less liable to crack the jars. Either wooden or aluminum scoops can be used with lead-lined tanks.

54. Cutting Out Plates.—If it is necessary to remove individual plates from a cell, a full charge should first be given. The plates can be conveniently stored in the free spaces at the ends of near-by cells or in a separate jar or tank filled with electrolyte; but positive and negative plates should not be brought into contact with each other nor with the lead lining of the same tank. If more convenient, positive plates can be removed and allowed to dry in the air without washing or other special precaution. If it is necessary to permit negative plates to dry, they should first be thoroughly washed with pure water to remove all electrolyte. A fully charged negative plate, especially when comparatively new, if allowed to dry in the air, will oxidize so rapidly as to produce considerable heat. If this heat becomes excessive, the plates should be sprayed with cold water. Negative plates thus discharged in the air require a prolonged overcharge, similar to the initial charge, when again put in service, which operation subjects the positive to excessive overcharge; negatives should therefore be kept immersed in electrolyte, if possible.

55. Putting Battery Out of Commission.—If the use of the battery is to be entirely discontinued for a period not longer than 9 months and it is not practical to charge at least once a month, care should be taken that an overcharge is given just before the idle period. Water should be added to the cells during the overcharge so that the gassing will insure thorough mixing. The level of the electrolyte should be about ½ inch from the top of the jars. After the overcharge is completed, the operator should make sure that all the cell covers are in place and should remove the battery fuses. Though not likely, the level of the electrolyte may, owing to excessive evaporation during the idle period, fall below the top of the plates; if this should occur, water must be added to keep them covered; if in a place where freezing is apt to occur, the electrolyte should be stirred after adding the water to insure thorough mixing.

If the battery is to be entirely out of service for more than 9 months, the procedure is as follows: After thoroughly

charging the cells, the electrolyte, which may be used again, is siphoned into thoroughly clean glass receptacles. As each cell is emptied, it is immediately filled with fresh, pure water, and when all the cells are filled, the battery is allowed to stand for 12 to 15 hours. The water is then siphoned out of each cell, after which the battery can be allowed to stand indefinitely. Any considerable sediment in the cells should be removed before it dries. If wooden separators are used, they are discarded, and replaced by new ones when the battery is put into service again.

56. Returning Battery to Commission.—If, in taking a battery out of service, the electrolyte has not been withdrawn, the battery can be returned to service by adding water, if needed, to the cells and overcharging the battery until the specific gravity of the electrolyte in the pilot cell has ceased to rise during a period of 5 hours.

If the battery has been standing without electrolyte, new wooden separators are installed and the cells then filled with electrolyte of 1.210 specific gravity. If the old electrolyte has been saved, only enough new electrolyte to replace any loss is added. The battery is then charged for 35 hours at the normal rate, or for a proportionately longer time at a lower rate. If the specific gravity of the electrolyte is low after the first charge, it should be restored to standard by the addition of acid.

57. Sulphation.—As stated in describing the reactions in the lead cell, Art. 4, sulphate of lead is formed in the active material of the plates during discharge. Under normal conditions, this sulphate is in a very finely divided state, and is readily decomposed by the electric current during charge. If the plates are allowed to remain in the electrolyte in a discharged condition for a considerable length of time, especially after an exhaustive discharge at low rate, a condition that may result, for example, from a short-circuit or a partial short-circuit in the cell, these normal and finely divided sulphate particles coalesce into larger masses, which are hard and crystalline and are much more difficult to decompose.

The remedy for this objectionable sulphation is a prolonged charge at not greater than half the normal rate. Higher rates do not hasten the process, but merely produce unnecessary heat and gassing.

58. Lead Burning.—In making joints between lead and lead, repairing tank linings, etc., solder cannot be used, because it is subject to attack and corrosion by acid. For such work, a process called *lead burning* is employed, requiring a blowpipe with a flame produced by the admixture of hydrogen and air under pressure. The supply of each is controlled by an independent stop-cock. The hydrogen is produced in a hydrogen generator by immersing scraps of zinc or iron in dilute sulphuric acid. Ordinary illuminating gas is sometimes used instead of hydrogen, but the hydrogen flame is hotter and more effective. Compressed air is usually obtained by forcing air into a receiver with a hand pump.

In lead burning, no flux of any kind is used, but the surfaces to be joined are partly fused with the blowpipe and the space between is filled by melting down a strip of lead drop by drop. Special forms, such as burning tongs or iron blocks, are used to retain the molten metal in place while cooling. Seams and repairs for tank linings are made in a similar manner; but, on account of the thinness of the sheet lead, a much greater degree of skill is required than for burning plate lugs, connectors, etc., and work on tank linings should not be undertaken until considerable experience and skill has been acquired.

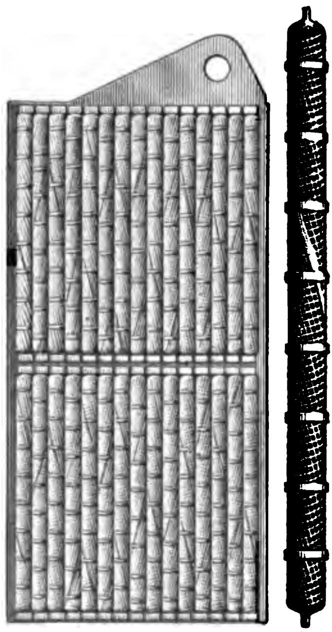
A lead-burning apparatus in which the electric arc furnishes the heat has also been developed. Current for the arc is obtained from two or more cells of the battery on which the work is being done.

NICKEL-IRON-ALKALINE CELL

CONSTRUCTION

59. Plates.—The positive plate, Fig. 28 (*a*), of the nickel-iron cell consists of a number of hollow tubes, or pencils, of perforated steel, nickel-plated, supported vertically in a nickel-plated steel grid. The pencils, Fig. 28 (*b*), are made of steel ribbon wound spirally with overlapping riveted seams, and are reinforced at intervals by steel bands. The active material consists of nickel peroxide and flake nickel tamped into the tube in alternate layers, the flake nickel being added to increase the conductivity.

The negative plate, Fig. 29, consists of rectangular pockets of perforated nickel-plated steel supported in a nickel-plated steel grid, the pockets being filled with finely divided iron oxide, which is reduced to metallic iron by the initial charge.



(*a*) (*b*)

FIG. 28

60. Assembly.—As in the lead cell, the positive and negative plates of the nickel-iron cell alternate, with negatives outside, there being one more negative than positive. The plates of each cell are assembled into positive and negative groups by bolting the corresponding lugs together and to the terminal

posts by means of steel connector rods with clamping nuts at each end, the plate lugs being spaced apart by steel washers. All steel parts are nickel-plated. Fig. 30 shows the plates of one cell assembled.

61. Separators and Electrolyte.—The plates are separated from each other by vertical strips of hard rubber, square in section, inserted with their vertical edges against the plates, as shown in Fig. 31, which is a view of a cell from above.

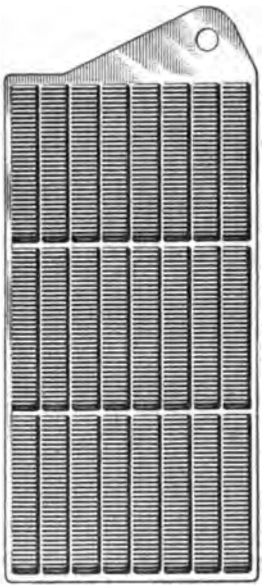


Fig. 29

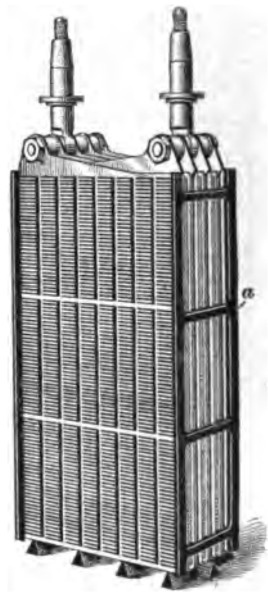


Fig. 30

Sheets of hard rubber are inserted between the outside negative plates and the jar, and hard rubber bridges *a*, Fig. 30, notched to receive the vertical edges of the plates, serve to separate these edges from the sides of the jar. The plates rest on hard-rubber bridges on the bottom of the jar, as shown in Fig. 30.

The electrolyte is a dilute (21 per cent.) solution of potassium hydrate (caustic potash), specific gravity approximately 1.200. A small amount of lithia (lithium hydroxide) is added.

62. Container.—The container of the nickel-iron cell is a box made of nickel-plated sheet steel, corrugated to give added stiffness, the cover being welded on after the element is in place. The two terminal posts *a* and *b*, Fig. 32, pass through circular openings provided with rubber bushings. Another opening in the cover, used for filling the cell, is closed by a spring cap containing a valve *c* that allows the gases

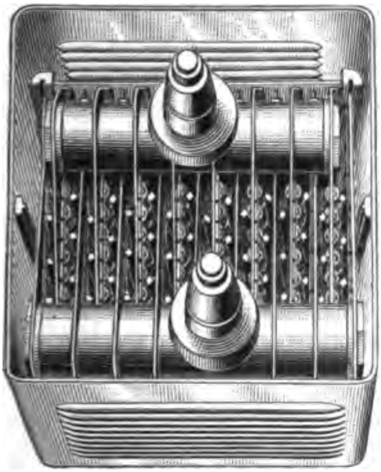


FIG. 31

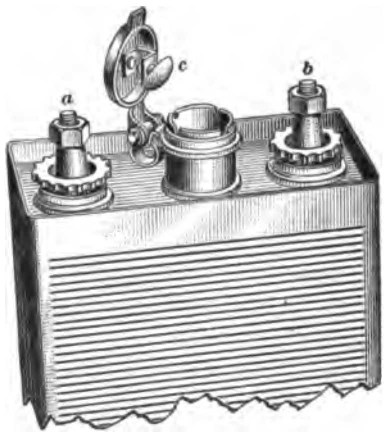


FIG. 32

to escape during charge, but excludes the external air. In an earlier design, there were two openings in the cover, one for filling and the other for the vent valve.

CHARACTERISTICS OF THE NICKEL-IRON CELL

63. Capacity.—The rated capacity of the nickel-iron cell is based on a 5-hour discharge rate. The actual capacity in ampere-hours, however, is but little affected by variation of discharge rate, provided no limit is set to the final voltage. In order to obtain maximum ampere-hour capacity at the higher rates, the final voltage must drop to a point too low for many classes of service.

Though the rated capacity is obtained by charging at the normal 5-hour rate for about 7 hours, it is possible, by giving the cells an excessive overcharge (16 hours at normal rate), to obtain on the subsequent discharge an increase in capacity of about 25 per cent. This excess is therefore obtained at a sacrifice in efficiency.

64. Voltage.—The open-circuit voltage of the nickel-iron cell is about 1.5 volts when fully charged. After a substantial discharge, the open-circuit voltage is restored only very slowly, and never completely until a freshening charge has been given.

In Fig. 33 are curves that show charge and discharge voltages of the nickel-iron cell at normal rate. The discharge curve,

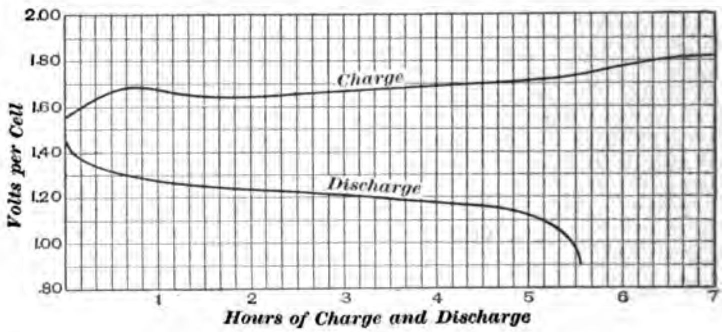


FIG. 33

as shown, is carried to .9 volt, though the normal-rate discharge is seldom carried below 1 volt in practice. The manufacturers recommend providing a charging voltage of 1.85 per cell. In Fig. 34 are shown discharge curves of the Edison cell at the various rates given in Table I. The cell temperatures for these curves are probably high because heat is developed in the cell during charge and discharge.

In Fig. 35 are curves that show the initial, average, and final voltages of the Edison cell at various discharge rates as compared with similar characteristics of the lead cell. The comparison is made between 60 nickel-iron cells and 42 lead cells to obtain practically the same open-circuit voltage.

65. Temperature.—The effect of temperature on the capacity of the nickel-iron cell is peculiar. Starting from a cell temperature of 100° F. and reducing the temperature gradually, the capacity falls off slowly about 10 per cent. until the temperature is reduced to a certain critical point, beyond which a few degrees further reduction of temperature reduces the capacity rapidly to about 10 per cent. of normal. The critical temperature at which this change takes place depends on the rate. At the 5-hour rate, it is about 40° F.; at twice the 5-hour rate, it is between 50° and 60° F. It should be noted that these are cell temperatures. Inasmuch as considerable heat is developed during both charge and discharge, the cell temperature is usually considerably higher than that of the outside air, especially if the battery compartment is designed to retain the heat.

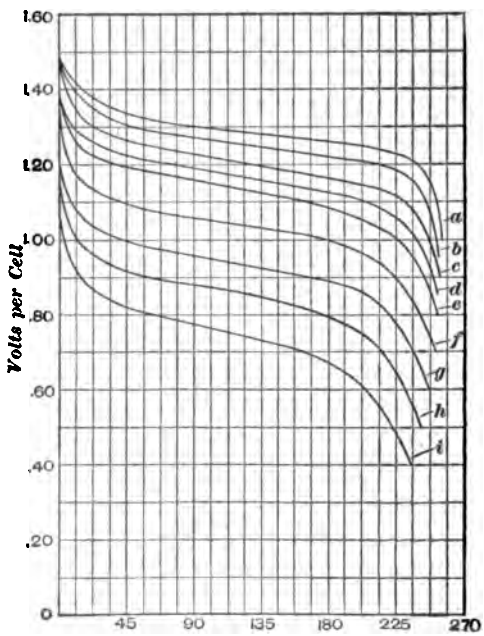


FIG. 34

66. Resistance and Efficiency.—The internal resistance of the nickel-iron cell is such as to cause a drop of approximately 7 per cent. of the open-circuit voltage with an increase of current equal to the 5-hour rate. At ordinary operating temperatures, the internal resistance of a battery of Edison cells is approximately three times that of a lead cell of the same capacity and voltage, and this ratio is increased at lower temperatures.

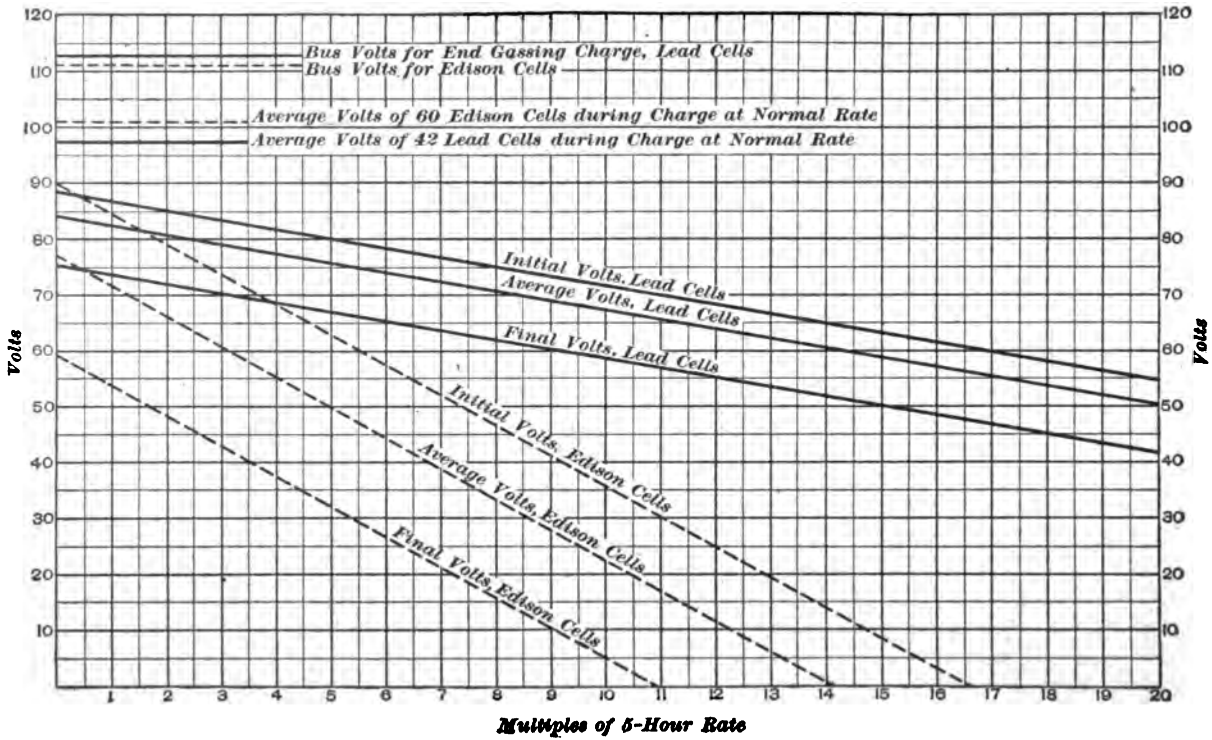

Bus Volts for End Gassing Charge, Lead Cells
Bus Volts for Edison Cells
Average Volts of 60 Edison Cells during Charge at Normal Rate
Average Volts of 42 Lead Cells during Charge at Normal Rate
Initial Volts, Lead Cells
Average Volts, Lead Cells
Final Volts, Lead Cells
Initial Volts, Edison Cells
Average Volts, Edison Cells
Final Volts, Edison Cells
Volts
Multiples of 5-Hour Rate

FIG. 35

The efficiency of the nickel-iron cell is lower than that of the lead cell under similar conditions. Not only is the difference in voltage between charge and discharge proportionately greater in the nickel-iron cell, but the ampere-hour efficiency is low on account of the gassing that occurs during the entire charging period. A watt-hour efficiency of 50 to 60 per cent. in commercial operation is about as high as can be expected,

TABLE I

DISCHARGE VOLTAGES, EDISON CELL

Curve	Rate of Discharge (Multiple of Normal)	Average Voltage	Hours of Discharge
a	$\frac{1}{3}$	1.272	17.040
b	$\frac{2}{3}$	1.240	8.475
c	1	1.203	5.690
d	$1\frac{1}{2}$	1.165	3.740
e	2	1.116	2.810
f	3	1.021	1.852
g	4	.921	1.375
h	5	.836	1.083
i	6	.731	.875

and this figure may be reduced if an attempt is made to utilize the maximum capacity of the battery.

67. Advantages and Applications.—The principal advantages of the nickel-iron cell are durability, mechanical ruggedness, and ability to withstand neglect and abuse without injury. Life curves published by the manufacturers as a result of laboratory tests show a maximum of 1,100 complete discharges. The cell is not injured by standing in a discharged condition, nor by excessive overcharge, provided excessive temperature is avoided. At low rates of discharge, the nickel-iron cell is considerably lighter than the lead cell for the same watt-hour output; but this difference in weight disappears as the rate of discharge increases, on account of the pro-

portionately lower voltage of the nickel-iron cell. The Edison cell is, therefore, best adapted for service at low discharge rates where the cost of charging current is low, where light weight is important, and where but indifferent care and attention are given. On the other hand, the nickel-iron cell is not well adapted for high rates of discharge, nor for service in which the cost of charging current is high, nor where a battery must retain its charge for a long period of time without recharging.

OPERATION AND CARE

68. Charging.—The state of charge of the nickel-iron cell cannot be determined by the density of the electrolyte, which does not change. Neither is the cell voltage or the amount of gassing a reliable guide. The only practicable method is to measure the output and input in ampere-hours, either by noting the rate in amperes and the time or by means of an ampere-hour meter. The manufacturers recommend a charge of 7 hours at normal rate after a discharge of 5 hours at the same rate, which is equivalent to 40 per cent. overcharge, in ampere-hours. The cell temperature should not be allowed to exceed 120° F.

The method of operation best adapted to the nickel-iron cell is that in which partial, or *boosting*, charges are given in the intervals between partial discharges. Boosting charges are particularly advantageous where the rate of discharge is sufficiently high to produce excessive polarization drop. The boosting charge quickly restores the cell voltage to normal, where otherwise it would remain abnormally low.

69. Changing Electrolyte.—The electrolyte in nickel-iron cells gradually deteriorates, owing to the absorption of carbonic-acid gas from the air. Deterioration, however, cannot be absolutely prevented, and, although this gas does not permanently injure the plates, it reduces the capacity of the cells temporarily. About once in 6 months the electrolyte should be completely renewed.

Water that is to be used for filling the cells must be protected from exposure to the air for any considerable length of time,

because water absorbs carbon dioxide (carbonic-acid gas) from the air. The local water supply, or even rainwater, which is very nearly pure, cannot safely be used for filling; distilled water protected from exposure to the air is generally necessary.

70. Special Precautions.—The containers of nickel-iron cells, being of metal, must be carefully insulated from each other and must be kept clean. The wooden crates in which the cells are supported, as well as the sides and floor of the battery compartment, must be kept clean and dry for the same reason. If the insulation between cells becomes defective from any cause, a small leakage of current will, by electrolytic action, puncture the steel containers.

The nickel-iron cell is gassing more or less at all times, whether charging, discharging, or standing on open circuit. These gases (oxygen and hydrogen) produce an explosive mixture. Care must therefore be taken to guard against bringing an exposed flame or producing an electric spark in the vicinity of the cells, unless the ventilation is very thorough.

71. Repairs.—The covers of nickel-iron cells are welded in place after the cells are assembled. The plates cannot therefore be removed from the containers, and whenever repairs are required it is necessary to return the cells to the factory for this purpose.

STORAGE-BATTERY CONTROL AND CONTROLLING APPARATUS

CONTROL OF CHARGE

72. The charging current of a storage battery can be controlled by means of a rheostat, by varying the voltage of the source of charging electromotive force, or by means of a booster.

73. Charging Through Resistance.—A charging rheostat is connected as at *r*, Fig. 36, where the voltage of the charging source is greater than that required for the number of cells in series. In such cases, the voltage of the charging source should be approximately equal to the final voltage of the battery at the end of charge; the rheostat serves to reduce this voltage to that required at the beginning of charge, and the resistance is gradually cut out as the charge proceeds.

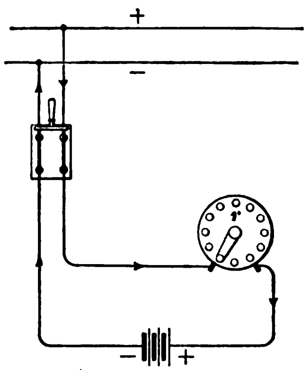


FIG. 36

A few small cells can be conveniently charged from a lighting circuit through lamp resistance. The current consumption of the lamps will then determine the charging current. Fig. 37 shows a method of connecting a battery to charge from a 110-volt circuit through five 110-volt, 16-candlepower, $\frac{1}{2}$-ampere lamps connected in parallel, the charging current being practically $5\times\frac{1}{2}=2\frac{1}{2}$ amperes. The charging current passes through the switch *a*, the fuses *b*, the lamps, the battery *c*, and the ammeter *d*, if one is used. The lamps may be connected in either lead to the battery.

Fig. 38 shows a battery connected to charge from a 500-volt circuit through five series of lamps, each series consisting of five 110-volt, ½-ampere lamps connected in series. In this case, the charging current will be a little less than 2½ amperes, because 550 volts is required to send ½ ampere through a series of five 110-volt, 16-candlepower carbon lamps.

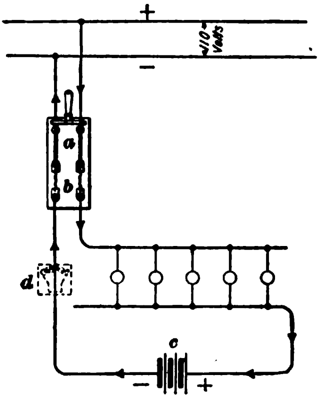


FIG. 37

This method of varying the charging current by varying the number of lamps, or series of lamps, in parallel is practicable only where the voltage of the cells is insignificant compared to that of the circuit. If, in the arrangement shown in Fig. 37, there are 25 cells in series, having a voltage between 55 and 65 while charging, the voltage across the lamps will be between 55 and 45, or about half the normal lamp voltage. Only half the normal amount of current will then be transmitted through the lamps, provided their resistance remains constant. But the resistance of a carbon-filament lamp increases as the amount of current through it decreases, while the resistance of a tungsten filament decreases as the current is reduced, and allowance must be made for this. The charging current is best determined by connecting an ammeter in circuit.

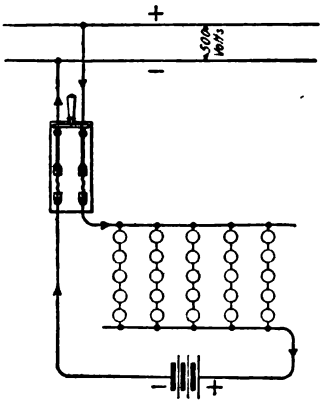


FIG. 38

74. In many small plants for isolated lighting, the battery is divided into halves, which are charged in parallel through fixed resistances and connected in series for discharge. Switchboard connections for such a system are shown in Fig. 39. The generator (not shown) is connected to the bus-bars through

a switch and fuses. With the double-pole, double-throw battery switches *a* and *b* in the upper positions, the batteries are, through the wire *c*, connected in parallel across the bus-bars. The main charging current then passes from the positive bus-bar, dividing at *d*, through the batteries and the fixed resistances *e* and *f*. Small portions of the charging current also pass through the pilot lamps *g* and *h*, which, by their

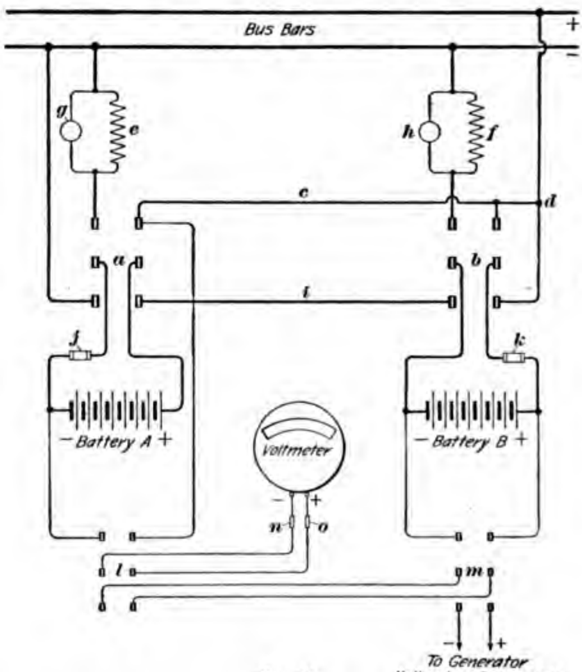


Fig. 39

degree of brilliancy, serve to show roughly the state of charge of the batteries, becoming dimmer as the charge progresses. With the battery switches in the lower positions, the batteries are, through the wire *i*, connected in series between the bus-bars. The fuses *j* and *k* protect the batteries from excessive current during both charge and discharge. The double-pole, double-throw voltmeter switches are shown at *l* and *m*. With the switch *l* in its upper position, the voltmeter indicates the

voltage between the terminals of battery A, during charge; with switch l in its lower position and switch m in its upper position, the voltmeter shows the voltage across battery B during either charge or discharge; with each voltmeter switch in its lower position, the voltage of the generator is indicated. The voltmeter is protected by fuses n and o.

This system avoids the necessity of installing a generator of specially high voltage, and the generator can always be operated at normal lamp voltage, even when charging the battery, but the current required for charging the entire battery is twice the charging rate of the cells.

75. Charging by Raising Generator Voltage.—In some cases, especially in small isolated plants for residence lighting, the battery is charged by raising the generator voltage at a time when no lights are required, and the high voltage is not objectionable. If a few lights should be required during such a charge, the voltage can be reduced for these by a rheostat or, preferably, by *counter-electromotive-force cells* (described in Art. 85) connected in opposition to the main battery.

Connections for this system of charging are shown in Fig. 40. If no lighted lamps are required while charging, the switch a is opened and the double-pole, double-throw switch b is closed to the left, connecting the main battery directly across the terminals of the generator c. If lamps are to be used while charging, the switch a is left closed and the switch b is thrown to the right. The generator is then connected directly across the bus-bars; but the voltage of the counter-electromotive-force cells assists that of the generator in charging the main battery, and the voltage of the generator can be lowered by means of the field rheostat e to a value low enough for the proper operation of the lamps. With the battery switch a closed and the generator switch b open, the bus-bars receive the external voltage of the main battery minus the counter voltage of the cells d and the resistance drop in them; also, the cells d then receive a charging current. The counter voltage of the cells d and the drop in them can be varied by moving the switch blade f, which alters the number of counter-

electromotive-force cells in circuit. An ammeter *g* indicates the current output of the generator; an ammeter *h* indicates the charging or discharging current, as the case may be, of the battery.

The connections of the voltmeter *i* are not shown completed in Fig. 40, but the wiring is actually so arranged that, by means of a voltmeter plug arranged as shown at *j*, voltmeter readings can be taken as follows: *1*+ and *1*−, generator voltage; *2*+ and *2*−, bus-bar voltage; *3*+ and *3*−, main

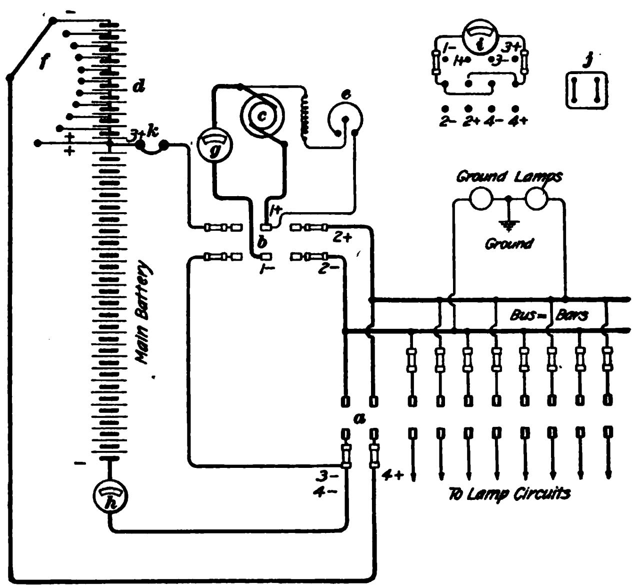


FIG. 40

battery voltage; *4*+ and *4*−, main battery voltage less counter-electromotive-force-cell voltage—all as indicated by the numerals in the illustration.

The various circuits of Fig. 40 are protected from overload by fuses. An automatic underload switch *k* prevents the charging current to the main battery from falling below a certain predetermined value.

The ground lamps serve to indicate a ground on either side of the system. Ordinarily, both lamps burn dimly, but with

equal brilliancy. If a ground occur on either bus-bar or on the conductors connected with it, the lamp connected to that bus-bar will be extinguished and the other lamp will burn at full brilliancy.

76. Charging Through Booster.—In larger installations, the battery is usually charged by means of a **booster**, which is an auxiliary generator whose voltage is added to that of the main generator or other source of current in order to provide the additional voltage required for charging the battery.

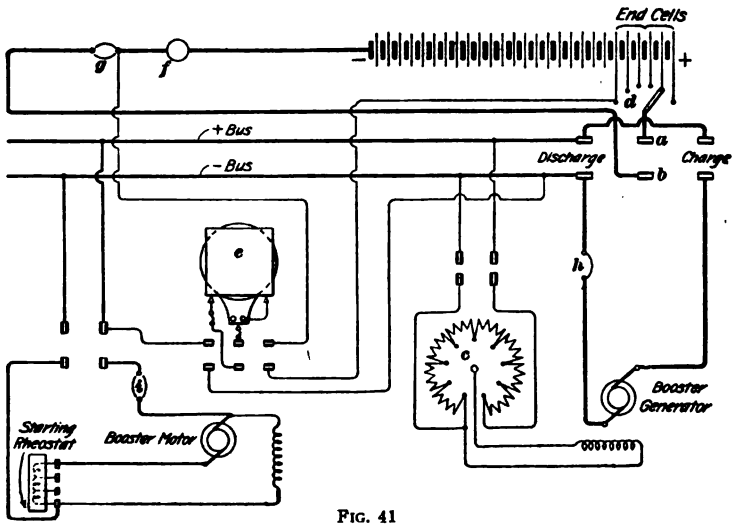


FIG. 41

This method of charging is preferable to either of the other two methods for batteries of large capacity, inasmuch as it obviates the rheostatic losses and permits current for lighting or other purposes to be taken directly from the main dynamo at normal voltage while the battery is being charged through the booster. This booster is usually direct-connected to a motor but may be belt-driven if convenient.

The system of connections for charging through a booster is shown in Fig. 41. The generator (not shown) is connected, through a switch, to the bus-bars. The battery is connected to the middle posts *a* and *b* of a double-pole, double-throw

switch. When this switch is closed at the right, charging current passes from the positive bus-bar, through the battery, through the booster generator, to the negative bus-bar. In the opposite, or discharge, position of the double-throw switch, the battery is connected directly across the bus-bars.

The field excitation of a booster must be under such control that the booster voltage can be varied from zero to the maximum. The booster cannot be self-excited, as the voltage would become unstable at low field saturation. The field is therefore separately excited from the main bus, a three-terminal rheostat *c*, Fig. 41, being used. This rheostat is connected directly across the circuit, and has a few high-resistance steps at one end to reduce the continuous flow of current. One field terminal is connected to one side of the circuit and to one terminal of the rheostat winding, and the other terminal is connected to the rheostat arm, so that when this arm is at one extreme of its travel, the field winding is connected across full bus voltage, while when the arm is at the other extreme, the field winding is short-circuited, and the excitation is then reduced to zero.

The battery of Fig. 41 has five end cells that can be cut into or out of circuit, one at a time, by means of the end-cell switch *d*. The use of end cells is described under the heading Control of Discharge.

Fig. 41 also shows a recording voltmeter *e* that can be connected, by means of a double-pole, double-throw switch across either the main battery (exclusive of the end cells) or the bus-bars. This is standard practice in battery installations of considerable size.

An ammeter *f* indicates the current output or input of the battery, and a circuit-breaker *g* protects it from overload. An automatic underload switch *h* prevents the charging current from falling below a predetermined value. A circuit-breaker *i* protects the booster motor from overload.

CONTROL OF DISCHARGE

METHODS OF CONTROL

77. In many small plants where the discharge rate is low, no control of the discharge voltage is provided, the variation from the beginning to the end of discharge not being objectionable. Where control of the discharge voltage is required, three different methods are used: by means of end cells, by means of counter-electromotive-force cells, and by means of a booster.

END-CELL CONTROL

78. Principle of End-Cell Control.—End-cell control consists in the variation of the discharge voltage by cutting in or out one or more cells at one end of a series. The method is illustrated in its simplest form in Fig. 42, in which *A* is

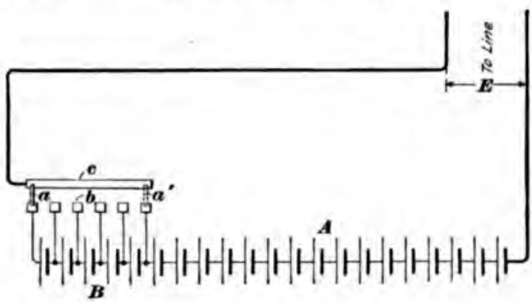


FIG. 42

the main battery and *B* a number of cells from each of which connection is made to the contacts *b* of an end-cell switch. A contact piece is arranged so that it can be moved to any of the contacts *b* from position *a* to *a'* by means of a suitable mechanism, and the number of cells in use thereby varied. When the battery has been fully charged, the end cells are cut out of circuit and the contact occupies the position *a'*. As the voltage runs down, the contact is moved to the left

and fresh cells are cut in, thus maintaining the voltage E at the desired amount.

End-cell control is adopted where changes of load take place slowly and there is ample time for hand control, as, for example, in electric-lighting service. The end-cell switch can be operated directly by hand for smaller installations, but is generally motor driven with remote control for larger installations.

79. Hand-Operated End-Cell Switches.—In order to avoid opening the circuit when the arm, or brush, of an end-cell switch passes from point to point, and at the same time prevent short-circuiting the cell or cells connected across adjacent points, auxiliary contacts *a*, Fig. 43 (*a*) and (*b*), are provided; these are connected through a suitable resistance *b* either to the traveling arm *c* or to the stationary contacts.

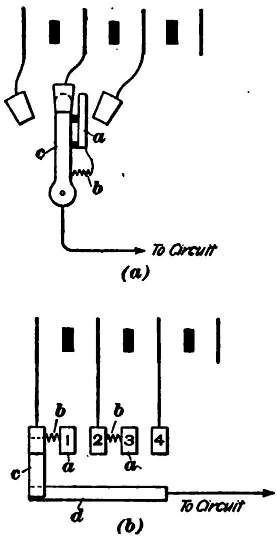


FIG. 43

Hand-operated cell switches for 50 to 500 amperes, inclusive, are of the round, or dial, pattern, as shown in part in Fig. 43 (*a*). The auxiliary contact *a* is carried by the main arm *c*, from which the auxiliary arm is insulated, except through the resistance *b*. When the switch is turned either to the right or to the left, the stationary contacts are momentarily bridged by the main arm and the auxiliary, so that the circuit is not opened; yet a short circuit of one cell is prevented by the resistance. This resistance is sometimes in the form of a coil wound around the shaft on which the arm is mounted. The switch is mounted on a switchboard and operated by a handle, not shown in the illustration. Current is taken from the arm by a sliding contact on the back of the board.

Hand-operated switches of 500 to 1,000 amperes are of the horizontal type shown in Fig. 43 (*b*). The continuous contact

rail *d* is connected to any one of the series of points above by the traveling brush *c*, the motion of which is effected by a rack and pinion, the rack being stationary and the pinion carried by the handle (not shown), which moves with the brush. Contact points with no resistance between them, as *1* and *2*, are close enough together to be bridged by the traveling arm; but points connected by resistance, as *2* and *3*, cannot be bridged by the arm. This arrangement permits movement of the arm without opening the circuit or short-circuiting the cells.

80. Motor-Driven Cell Switches.—Motor-driven cell switches are of the horizontal type, similar to Fig. 43 (*b*), consisting of a row of contact points with auxiliary contacts between and a horizontal conducting rail, the traveling arm usually being driven by a long, horizontal screw rotated by an electric motor. The auxiliary contacts, which prevent short-circuiting the intervening cells while the arm, or brush, is passing from one contact point to the next, consist of carbon blocks. The brushes usually also carry carbon trailers on each side.

In one type of motor-driven end-cell switches, the motor is controlled by means of two electromagnets. Each magnet, when excited, operates a switch to connect the motor armature across the bus-bars—one switch for one direction of motor rotation and contact-arm travel, and the other for the opposite direction. The magnets are selectively excited by means of a single-pole, double-throw control switch at the switchboard, so that the operator can start the motor in either direction at will. A cam geared to the motor and designed to make one revolution while the brush is traveling from one point to the next engages the active switch as soon as it is closed by the electromagnet, preventing it from opening on interruption of the exciting current of the magnet until the brush comes in full contact with the next switch point. Thus, the operator cannot stop the brush between two points of the switch. At each end of the cell switch is a limit switch, mechanically opened by the brush, to interrupt the exciting

circuit of one of the electromagnets and prevent further travel of the brush in that direction.

Another arrangement has on the switchboard an illuminated dial carrying a series of numbers representing the several end cells. This dial can be set by the operator at the point corresponding to that to which the cell-switch brush shall travel, and the brush will thereupon be driven by the motor to the desired point and stop there automatically without further attention on the part of the operator.

In another make of end-cell switch the traveling brush is moved by a complicated arrangement of bars and pawls.

81. Control by Two Cell Switches.—When a battery whose discharge voltage is controlled by end cells is charged

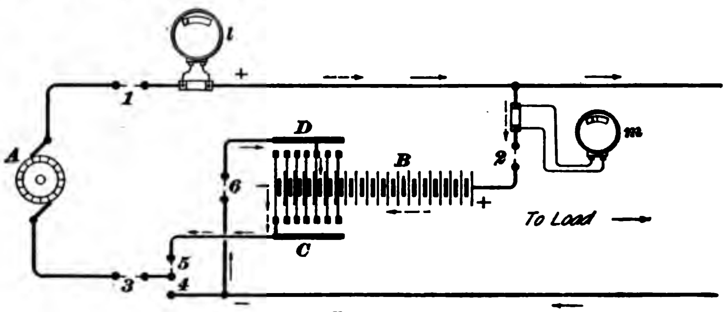


FIG. 44

by raising the dynamo voltage, a second end-cell switch is sometimes added to provide voltage for lamps that may be required during the charging period, the voltage of the dynamo being too high for the lights. The connections for this arrangement are shown in Fig. 44. Switches *1*, *2*, and *3* are closed and the double-throw switch *4*, *5* is in the upper position; the battery is charging, and the path of the charging current is represented by the dotted arrows. At the same time, the generator *A* is furnishing current to the line, as indicated by the full-line arrows. With the end-cell switch *D* in the position shown, the pressure between the lines outgoing to the load is that of the main battery *B* plus that of two end cells, while, owing to the position of switch *C*, the pressure of the generator

must be high enough to charge the entire battery, including the end cells. Ammeters *l* and *m* measure the generator current and battery current, respectively.

82. Number of End Cells in Series.—The number of end cells in series is the difference between the total number of cells in series in the entire battery and the minimum number permissible in the main battery. The total number of cells in series, including end cells, is determined by dividing the bus voltage to be maintained by the final voltage per cell at the end of discharge (Art. **31**). In this connection, it may be noted that the bus voltage can frequently be allowed to drop below normal at the end of discharge, especially where the chances of a complete discharge at maximum rate are quite remote; this is standard practice in designing large battery installations for standby service in central lighting stations.

If the battery is to be disconnected from the bus while charging, the number of cells in series in the main battery may be found by dividing the lowest allowable bus voltage by the floating voltage (see Art. **30**). If the battery must be connected to the bus while charging, the number of cells in the main battery may be found by dividing the bus voltage by the maximum cell voltage at the end of charge (Art. **32**).

For example, if a bus voltage of 115 is to be maintained, the total number of cells in series, including end cells, must be $115 \div 1.75 = 66$. If the battery is to be disconnected from the bus while charging, the number of cells in series in the main battery will be $115 \div 2.1 = 55$, assuming a floating voltage of 2.1 per cell. If the battery must be connected to the bus while charging, the main battery will contain $115 \div 2.5 = 46$ cells in series, assuming a maximum cell voltage of 2.5 at the end of charge. In the first case, therefore, the number of end cells in series will be $66 - 55 = 11$, and in the second case, $66 - 46 = 20$.

83. Grouping of End Cells.—In general, end cells are connected singly to the cell switch; that is, one cell across each pair of adjacent points. In special cases, as in batteries

for emergency standby service, the extreme cells are connected to the cell switch in groups of two or three to a point. This reduces the cost of the cell switch and the end-cell copper, and also reduces the time required to cut in the end cells in a high-rate emergency discharge.

84. Charging End Cells.—Since the end cells of a battery are cut in step by step during the discharge, some are not fully discharged and require less recharging than others. The charge is started with all cells in circuit, and the end cells are cut out step by step in the reverse order, as they become fully charged.

COUNTER-ELECTROMOTIVE-FORCE CELLS

85. In small installations, for residence lighting, etc., counter-electromotive-force cells are used instead of end cells for controlling the discharge voltage. The plates in these cells are merely grids without active material, and therefore have no capacity except that due to a thin coating of active material that gradually forms on the surface of the grids with use. The voltage of counter-electromotive-force cells opposes the discharge current, and is deducted from the voltage of the battery at such times as the beginning of discharge and during charge. Counter-electromotive-force cells do not always carry the charging current (see Fig. 40). As the battery voltage drops during discharge, the counter-electromotive-force cells are cut out of circuit step by step by means of an end-cell switch.

Counter-electromotive-force cells are preferable to a rheostat for this purpose, because the voltage drop in them is nearly constant, regardless of the current, whereas the drop of voltage in a rheostat is directly proportional to the current it carries, thus requiring a change of adjustment with change of load.

BOOSTER CONTROL

86. Line Batteries.—Storage batteries are frequently employed to smooth out automatically the fluctuations of load or voltage that are too rapid for hand control. The

simplest form of regulating battery is a *line battery* connected directly across the circuit at a place sufficiently remote from the source of power to introduce considerable line drop. If the load is variable, the voltage at the battery site will be variable, and this will cause the battery to charge and discharge. The number of cells in series is so chosen that the battery floats when the line voltage is at its average value. An increase of load then causes the battery to discharge, and a decrease causes it to charge. For example, if the average, or floating, voltage at the point of installation is 450, 214 cells in series are installed. If the 1-hour rate of the battery is 200 amperes, and the internal resistance drop at the 1-hour rate, including some polarization, is about 8 per cent. of the floating voltage, or 36 volts, then the equivalent internal

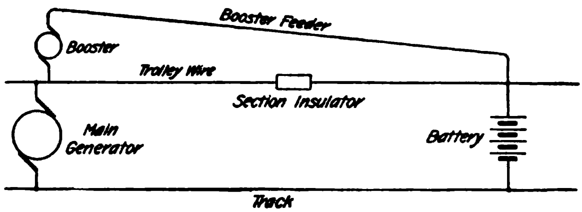


FIG. 45

resistance of the battery is 36÷200, or .18 ohm. If the resistance of the line conductors is 1 ohm, the fluctuations of load divides between the battery and the conductors in the ratio of 1 to 1.18; that is, the battery takes 1÷1.18, or about 85 per cent., of the fluctuations.

If the average voltage at the point where the battery is to be installed is too low for satisfactory operation, this voltage can be increased by the use of a *booster feeder;* a separate feeder extends from the power house to the battery station, as shown in Fig. 45, which represents, roughly, a railway system. A shunt-wound booster in series with the feeder at the power house raises the voltage.

87. Function of the Booster.—A line battery performs the dual function of reducing the fluctuations of voltage at the point where it is installed and of relieving the system of

a part of the load fluctuations in its vicinity. Similarly, a battery connected across the line at the source of power will regulate more or less if the source has a *drooping characteristic;* that is, if its voltage falls with increase of load and rises with decrease, as does that of a shunt-wound or a differentially wound generator. If, however, the voltage of the circuit is constant at the battery site, the battery cannot charge or discharge without some controlling apparatus to compel it to do so. The **regulating,** or **automatic, booster** is employed to control both the charge and discharge of a battery when the fluctuations of load are too rapid for hand control, as in the case of an electric-railway load or intermittent power service.

Two methods of connecting such a booster are used, giving rise to two types of booster, namely, the *series regulating booster* and the *constant-current booster.*

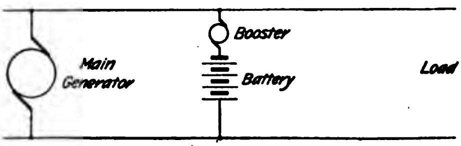


FIG. 46

88. The series regulating booster, or *reversible booster,* as it is sometimes called, is a generator run at constant speed and connected in series between the battery and the main bus or circuit to which both the main generators and the load circuits or feeders are connected, as shown in Fig. 46. This booster, therefore, carries the total battery current, and the direction of this current in the booster field determines the direction of the booster voltage. When the battery is neither charging nor discharging, its voltage is usually approximately the same as that of the bus, and the booster generates no voltage. When the battery is discharging, its voltage drops, and the booster voltage is added to that of the battery to compensate for the drop. When the battery is charging, its voltage rises, and the booster voltage is added to that of the line. The voltage of the booster and the current in its armature thus reverse in direction at the same time or nearly so. This scheme is used in electric-railway regulating batteries.

89. The **constant-current booster** is connected between the generator and the battery, with the fluctuating load directly across the battery terminals, as shown in Fig. 47. A unidirectional and substantially constant current is transmitted from the generator through the booster armature to the circuit to which the battery is connected. When the demand for current on this circuit exceeds this amount, the battery discharges to supply the deficiency. When the demand is less, the surplus charges the battery. The booster voltage varies in accordance with the changes of battery voltage with charge and discharge. This system is used principally to control the fluctuations of loads of electric elevators in office buildings, etc.

With the series regulating booster, the entire load is taken from one circuit, and the voltage impressed on this circuit

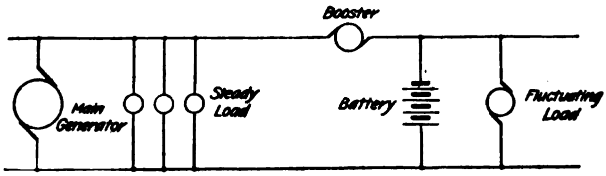


Fig. 47

is substantially constant, being that of the main bus to which the main generator is connected; with the constant-current booster, the lamp circuit and power circuit are separated, and the voltage impressed on the latter is variable, being that of the battery. The constant-current system is employed, therefore, only when the transmission distance is short and the drop of voltage under heavy load is not objectionable. The principal advantage of the constant-current system is the reduction in the size and the cost of the booster made possible when the average load is much smaller than the maximum load.

90. Carbon Regulator.—A device frequently employed for controlling automatically the voltage of a series regulating booster, to compel the battery to charge and discharge with fluctuations of load, is the carbon regulator, shown in perspective in Fig. 48 and diagrammatically in Fig. 49. The

regulator consists of two sets *a* and *b* of carbon disks so arranged on opposite sides of the fulcrum of a lever *c* that force applied to one end of the lever will compress one set and relieve the pressure on the other, thus producing a wide variation of contact resistance between the disks. The carbon piles are connected in series across the battery terminals *d* and *e*, Fig. 49, and the field winding of the booster exciter is connected between the middle point *f* of the battery and a point between the two sets of carbon piles. The pressure exerted on the carbon

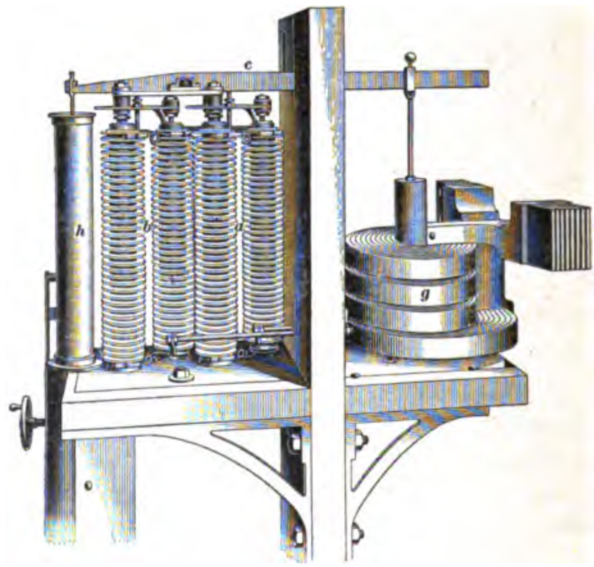


FIG. 48

piles is controlled by an adjustable spring at one end of the lever and a solenoid *g*, Figs. 48 and 49, at the other. The solenoid is connected in the main generator circuit and carries the total output of all of the generators.

When the output of the main generator is normal, the pull of the solenoid is balanced by that of the spring, the pressures on the two sets of carbon piles are equal, and their resistances are equal. There is then no current in the exciter field winding, the booster voltage is zero, and the battery

floats on the line, neither charging nor discharging. A small portion of any increase in load is supplied by the main generators, increasing the pull of the solenoid and thereby compressing one set *a* of carbon piles and relieving the pressure on the other set *b*. The equality of the resistances of the two sets of carbon piles is thus destroyed, and the exciter field winding receives current through the path *f–a–e*, Fig. 49, in such a direction that the resulting booster voltage aids the battery voltage. The battery then discharges and relieves the generators of all the increase in load, except the small part necessary to actuate the regulator. Upon decrease of load below normal, the regulator spring overcomes the pull of the solenoid,

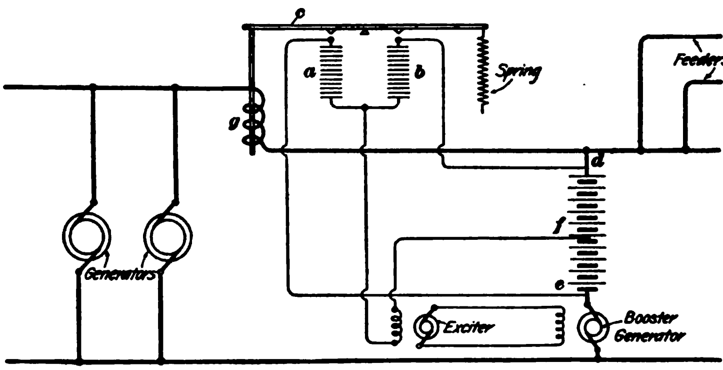


Fig. 49

and the resulting compression on set *b* of carbon disks sends current through the exciter field winding by the path *d–b–f*. The booster voltage is now built up in such a direction as to oppose the battery voltage, causing the battery to be charged. A substantially constant load on the generators is thus maintained.

In some installations, the carbon piles are connected across only a section of the battery; in others, the exciter is not used, and the regulating current passes directly through the booster field winding. In every case, however, the general principle of operation is the same.

In Fig. 48, the regulating spring is concealed in the cylindrical casing *h*. Adjustment of the tension of this spring is obtained by means of the hand wheel.

91. Reversing Rheostat for Booster Field.—Fig. 50 illustrates a special type of field rheostat used when the voltage of the booster is to be reversed and controlled by gradual steps in either direction. Equal resistances *A* and *B* are split into a number of sections and connected to the insulated segments *g*, as shown; *d* and *e* are stationary contact arcs, and a lever pivoted at *h* carries moving contacts *a* and *b* that bridge between the segments and the contact arcs. Terminals *x* and *y* are connected either to the bus-bars or to the

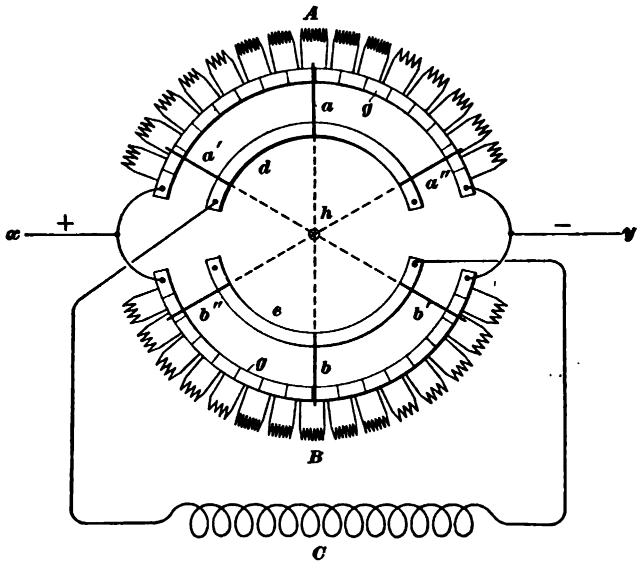


FIG. 50

battery terminals, and the arcs *d* and *e* are connected to the field winding *C* of the booster. The scheme of connections is the same as a Wheatstone bridge with the galvanometer replaced by the field *C*. When the lever is in the vertical position *a b*, there is no difference of potential between the field terminals, and the field is unexcited. As the lever is moved over toward the position *a'' b''*, the pressure across the field terminals is gradually increased until the extreme position of the lever is reached, and *e* is connected directly

to the + terminal and *d* to the − terminal. A movement of the lever in the reverse direction; that is, from the vertical position toward *a′ b′*, gradually increases the pressure across the field but in the reverse direction. This rheostat therefore allows the booster to be used as an aid either in charging or discharging, and also allows close regulation of the charging and discharging current. In order to make the waste of energy small, the central sections of the rheostat have a high resistance.

92. Compound Booster.—The voltage of a compound booster is controlled by a series winding and a separately

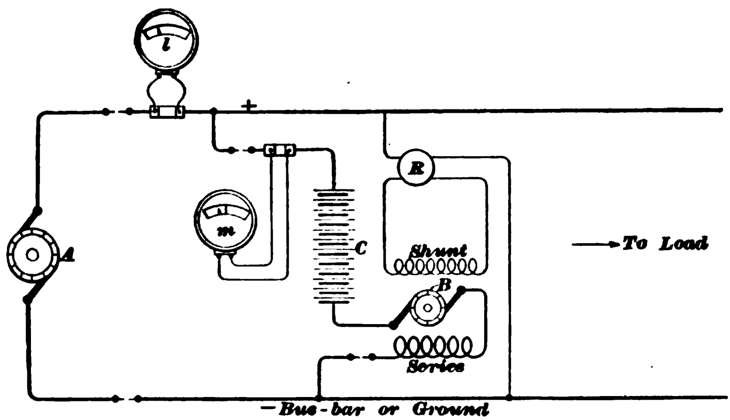


FIG. 51

excited shunt winding, the booster armature *B*, Fig. 51, and its series winding being connected in series between the battery and the line. The series winding is designed to give a booster voltage in the same direction as the current, and sufficient in value, for any given current, to compensate for the ohmic drop in battery voltage due to that current. The shunt-field excitation is adjusted by hand to compensate for those changes of battery voltage which are due to polarization or for changes in bus voltage. Since the direction of current in the shunt field may at times have to be reversed, a reversing field rheostat *R* is used for the shunt-field control. Ammeters *l* and *m* indicate the outputs of the generator *A* and battery *C*, respectively.

Inasmuch as this type of booster depends for automatic control on the charge or discharge of the battery to excite its series field, it cannot act as the original cause for such charge or discharge. This combination must therefore operate on a system having a drooping characteristic; that is, the line voltage must drop with increase of load. This variation of line voltage will start the battery charge and discharge, the booster acting to augment the action of the battery and maintain a more nearly constant voltage. The rheostat R is so adjusted that when the generator is delivering its normal load at normal voltage, the voltage of the booster plus that of the battery just equals the voltage of the generator; under these conditions there will be neither a charging nor a discharging current. If the load on the line increases, the voltage of the generator tends to drop on account of the increased load momentarily thrown on it. This allows the battery to discharge, and the discharging current through the series coils of the booster raises the combined electromotive force of the battery and booster, thus making the battery at once take such a share of the load that the electromotive force across the lines is restored to normal. On the other hand, a decrease in the external load below the normal tends to make the generator voltage increase. The battery then charges, and the charging current through the series-coils of the booster opposes the shunt coils, thus lowering the booster voltage and allowing the charging current to increase until the generator voltage comes down to normal. In actual working, the voltage of the system changes very slightly, as any tendency to change is checked by the operation of the battery and its booster.

This type of booster is sometimes used with a large line battery designed for sustained high-load discharge, as well as for regulating momentary fluctuations, especially where the variations of line voltage are not of sufficient range fully to utilize the battery capacity.

93. Counter - Electromotive - Force Booster. — The counter-electromotive-force booster requires an exciter *a*, Fig. 52, with a field *b* connected in series with the main generator *c*.

The exciter armature, in series with the booster field *d*, is connected across the bus-bars. Under average load conditions, the exciter develops a voltage equal to the bus voltage; then no current passes through the booster field winding, the booster voltage is zero, and the battery floats on the line. Any fluctuation of load changes the generator voltage, and consequently the current, in the exciter field winding, thus changing the voltage of the exciter to a value above or below that of the bus; the booster field winding then receives current in one direction or the other, causing the battery to either charge or discharge, depending on whether the load has decreased or increased.

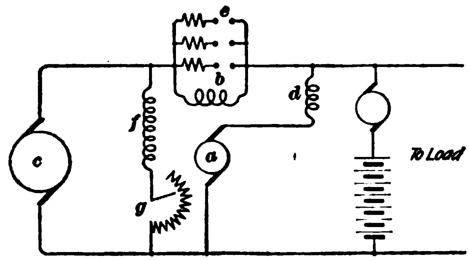


FIG. 52

To adjust the exciter voltage for different average loads, several shunts *e*, Fig. 52, are provided for connection across

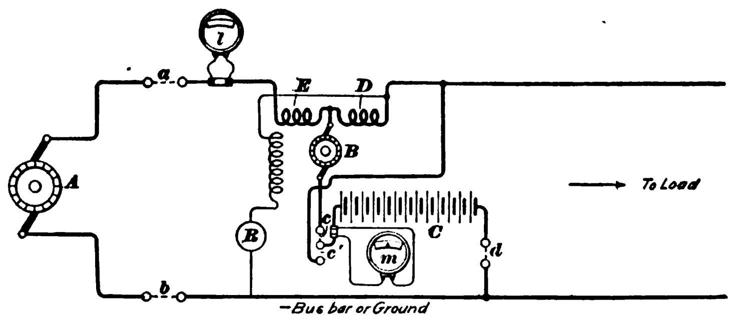


FIG. 53

the exciter field. Sometimes the adjustment is obtained by means of a shunt field winding *f* and a rheostat *g*.

94. Differential Booster.—The differential booster has two series field windings so connected that one *E*, Fig. 53, carries the current of the generator *A*, while the other *D* carries the total load current including the discharge current of the

battery C. The booster armature B is in series with the battery. The two series coils are designed to produce a booster voltage to cause the battery to discharge; the shunt field winding is designed to oppose the series windings. When the demand on the load circuit is equal to the desired average generator load, the shunt field is adjusted by means of a rheostat R to neutralize the series fields; the booster voltage is then zero and the battery neither charges nor discharges. Any increase of load, passing through the outside field D, produces a voltage suitable to make the battery discharge and relieve the generator of the increase. If the shunt-field adjustment is not quite perfect, part of the increase of load, falling on the generator, produces an increase of current in the inside series winding E, which then assists the outside winding D. If the load falls below normal, the magnetizing effect of the shunt field predominates, thus making the booster generate an electromotive force in the reverse direction and allowing the battery to charge. The load on the generator is therefore kept practically constant in spite of the fluctuations of the load delivered from the station.

Main generator switches are indicated at a and b, Fig. 53, and battery switches at c and d. With switch d closed and the single-pole, double-throw switch in the position c, the booster is in circuit; with this latter switch in position c', the booster is out of circuit. Ammeters l and m measure the generator and battery currents, respectively.

Because of the cost of the heavy series windings and cable connections, no new installations of differential boosters are being made, though some of the old installations are still in operation.

95. Series-Wound Constant-Current Booster.—A method of connections for the automatic control of the voltage of a constant-current booster is shown in Fig. 54.

The generator A supplies current to the bus-bars E and F to which the steady load is connected. The fluctuating load is connected to bus-bars G and H, and the booster armature B and series-field are connected in series between E and G. The

fluctuating load current does not pass through any of the booster windings as in the case of the compound and differential boosters; the booster carries only the average current supplied by the generator to the power system. An end-cell switch D is usually provided so that the battery can be operated on the lighting load only, the cells being cut in as the voltage drops. The booster is provided with a shunt winding, which sets up an electromotive force in the armature in a direction such as to aid the generator electromotive force. The series coils oppose the shunt coils and set up an electromotive force opposed to that of the generator. The current through the

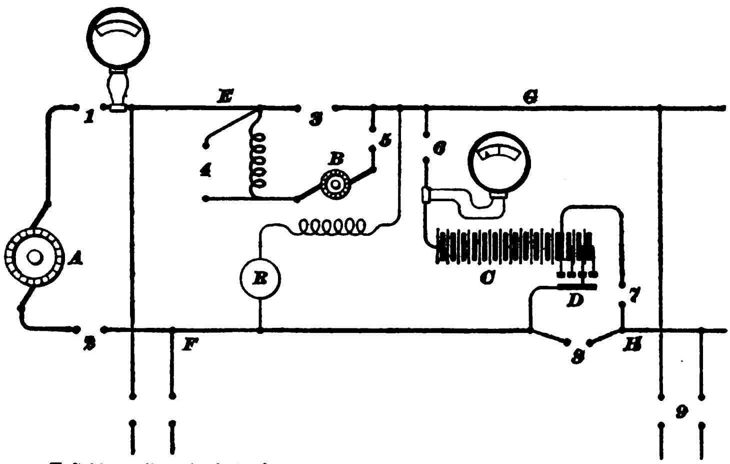


FIG. 54

booster is not reversed, because the only current through it is that supplied by the generator. Under ordinary operating conditions, switches *1*, *2*, *5*, *6*, and *7* are closed. Then, in case a heavy load comes on the power circuits, the tendency is for a heavy current to be delivered by the generator through the booster. The voltage across the terminals of the battery is equal to the generator voltage plus that of the booster; any increase of current in the series field causes a lowering of the booster electromotive force. The result is that the pressure across the battery terminals decreases, thus causing the battery to discharge and supply the extra demand

for current. Conversely, a decrease in the fluctuating load causes the battery to charge. The generator therefore delivers an approximately constant current; the irregularities due to the heavily fluctuating motor load are so smoothed out that the pressure supplied to the lamps is practically uniform.

If both loads must be operated directly from the generator, the battery and booster can be cut out as follows: The booster is shut down and switch *3* closed. Switch *3* cannot be closed while the booster is generating, because armature *B* would be short-circuited. Switch *5* is then opened and the booster thereby cut out of service. By opening switches *6* and *7* and closing switch *8*, the battery is cut out and the generator is connected directly with the load circuit. Switch *7* must be opened before *8* is closed; otherwise, the end cells will be short-circuited. If it is desired to cut off the fluctuating load and run the lights from the battery alone, switches *8* and *9* are opened and switch *6* is closed. This cuts off the fluctuating load and places the battery, with its end cells, in parallel with the generator, it being understood that the booster is now out of service. By opening switches *1* and *2*, the generator is cut off and the whole lighting load is carried by the battery, the regulation being effected by means of the end-cell switch. When the battery is to be given a full charge, the booster can be operated as a plain shunt generator by cutting out the series coils by means of the short-circuiting switch *4*.

This type of booster was formerly used for the regulation of fluctuating elevator loads in office buildings; some are yet in operation. The series-wound constant-current booster is still installed occasionally where the average load is small and the cost of the series winding is not excessive.

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NOTE.—In this Volume, each Section is complete in itself and has a number. This number is printed at the top of every page of the Section in the headline opposite the page number, and to distinguish the Section number from the page number, the Section number is preceded by a Section mark (§). In order to find a reference, glance along the inside edges of the headlines until the desired Section number is found, then along the page numbers of that Section until the desired page is found. Thus, to find the reference "Ampere, §24, p7," turn to the Section marked §24, then to page 7 of that Section.

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